

NASA Contractor Report 3345

NASA
CR
3345
pt. 2
c. 1

LOAN COPY: RETURN TO
APWL TECHNICAL LIBRARY
KIRTLAND AFB, N.M.

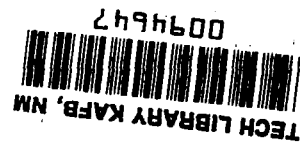
Electrostatic Protection of the Solar Power Satellite and Rectenna Part II - Lightning Protection of the Rectenna

TECH LIBRARY KAFB, NM
0094647

CONTRACT NAS8-33023
NOVEMBER 1980

NASA

NASA Contractor Report 3345



Electrostatic Protection of the Solar Power Satellite and Rectenna

Part II - Lightning Protection of the Rectenna

*Rice University
Houston, Texas*

Prepared for
Marshall Space Flight Center
under Contract NAS8-33023



National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1980

Table of Contents

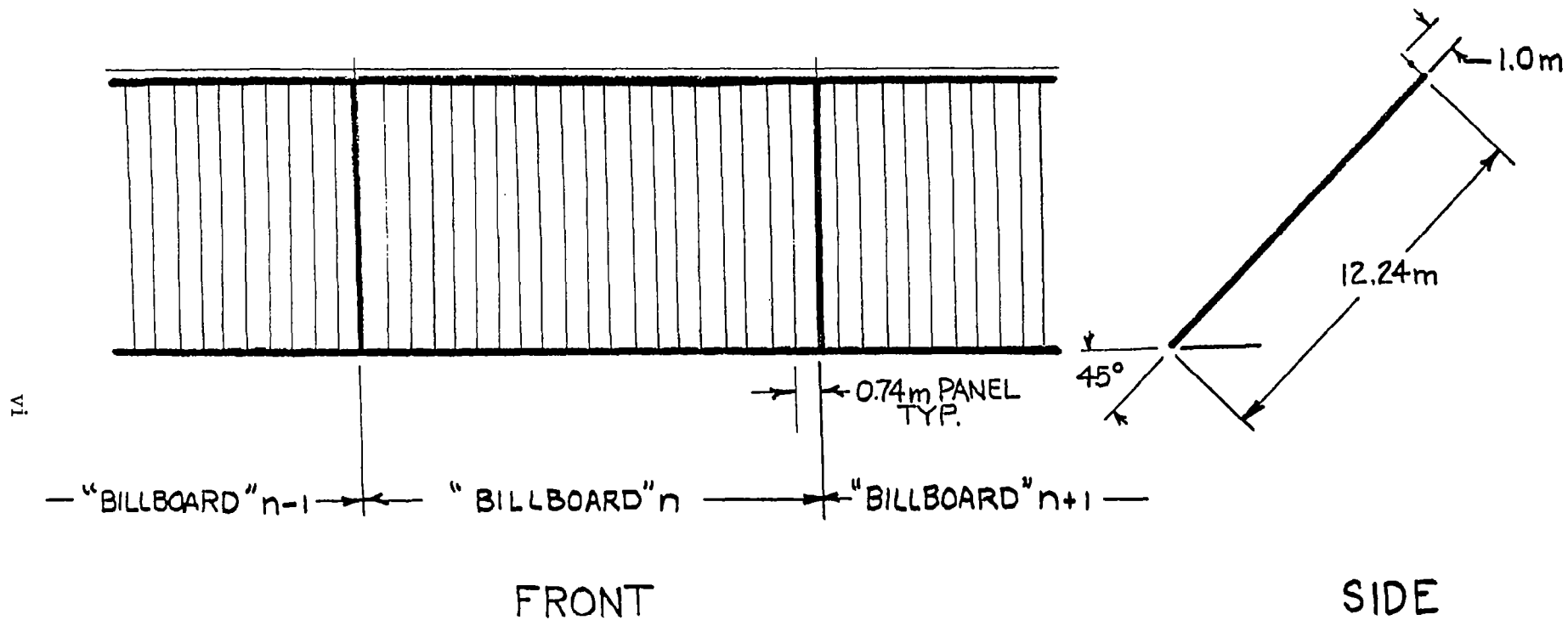
I. LIGHTNING ROD PROTECTION CAPABILITIES SUITABLE TO THE RECTENNA.....	1
II. SIMULATIONS OF LIGHTNING STRIKES TO THE SPS RECTENNA.....	17
III. GROUNDING CONSIDERATIONS FOR THE PROPOSED LIGHTNING PROTECTION SYSTEM..	28
IV. MATERIALS AND SPECIFICATIONS FOR LIGHTNING PROTECTION.....	35
V. ESTIMATE OF POWER LOSS FROM THE BEAM.....	37
VI. MICROWAVE DIODE FAILURES DUE TO INDUCED CURRENT TRANSIENTS.....	39
VII. COMPUTER SIMULATION OF ELECTROSTATIC FIELD AROUND AN SPS RECTENNA.....	41
VIII. COMPUTATION OF LIGHTNING ELECTRIC FIELDS.....	48
IX. COMPUTATIONS OF DIODE FAILURE.....	59
X. LIGHTNING PROTECTION FOR SERIES DIODE STRINGS.....	61
XI. CLOUD-TO-GROUND LIGHTNING DISTRIBUTION IN THE UNITED STATES.....	63

SUMMARY AND CONCLUSIONS

1. The very high lightning flash density in many parts of the United States and the large size of the SPS rectenna require us to incorporate lightning protection systems in the rectenna design.
2. A distributed lightning protection system is described in this report that will protect the rectenna components from direct lightning strike damage and will, in addition, provide reduced induced lightning effects in the power and control circuits.
3. The proposed lightning protection system should be incorporated as a structural member of the rectenna support system; viewed as such, the lightning protection system will not appreciably increase the total material requirements for the rectenna unless materials are used that are incapable of safely conducting lightning currents.
4. The lightning protection design places the conducting elements so that the microwave shadow cast by protection systems falls along the upper edge of the billboard on which it is mounted (and the lower edge of the next billboard to the north); these shadow areas are only a slight fraction of the collecting area, so the protection elements produce very little, if any, additional power loss to the rectenna as a whole.
5. Individually the microwave diodes are self-protecting with respect to "average" lightning and those near the center of the rectenna are safe from extreme lightning. However, the series connection of the diodes to form 40,000 V strings creates a protection requirement for the string. Standard surge protection practices are necessary for the string.
6. Electric power industries usually attribute 10% of the cost of power transmission equipment to lightning protection requirements. If this factor is not already included in cost estimates, it should be added.

SUMMARY OF THE RECOMMENDED LIGHTNING PROTECTION DESIGN

Based upon our research, computer simulations, and laboratory tests with a scale model, we recommend a distributed lightning protection system that employs a horizontal conducting member with points and grounds placed at every bay or billboard (14.69 meters apart). This configuration not only provides greater protection than other configurations that were evaluated, it is more easily integrated into the structural design of the rectenna. The recommended system is shown in Figure 1.



DISTRIBUTED LIGHTNING PROTECTION SYSTEM

FIGURE 1

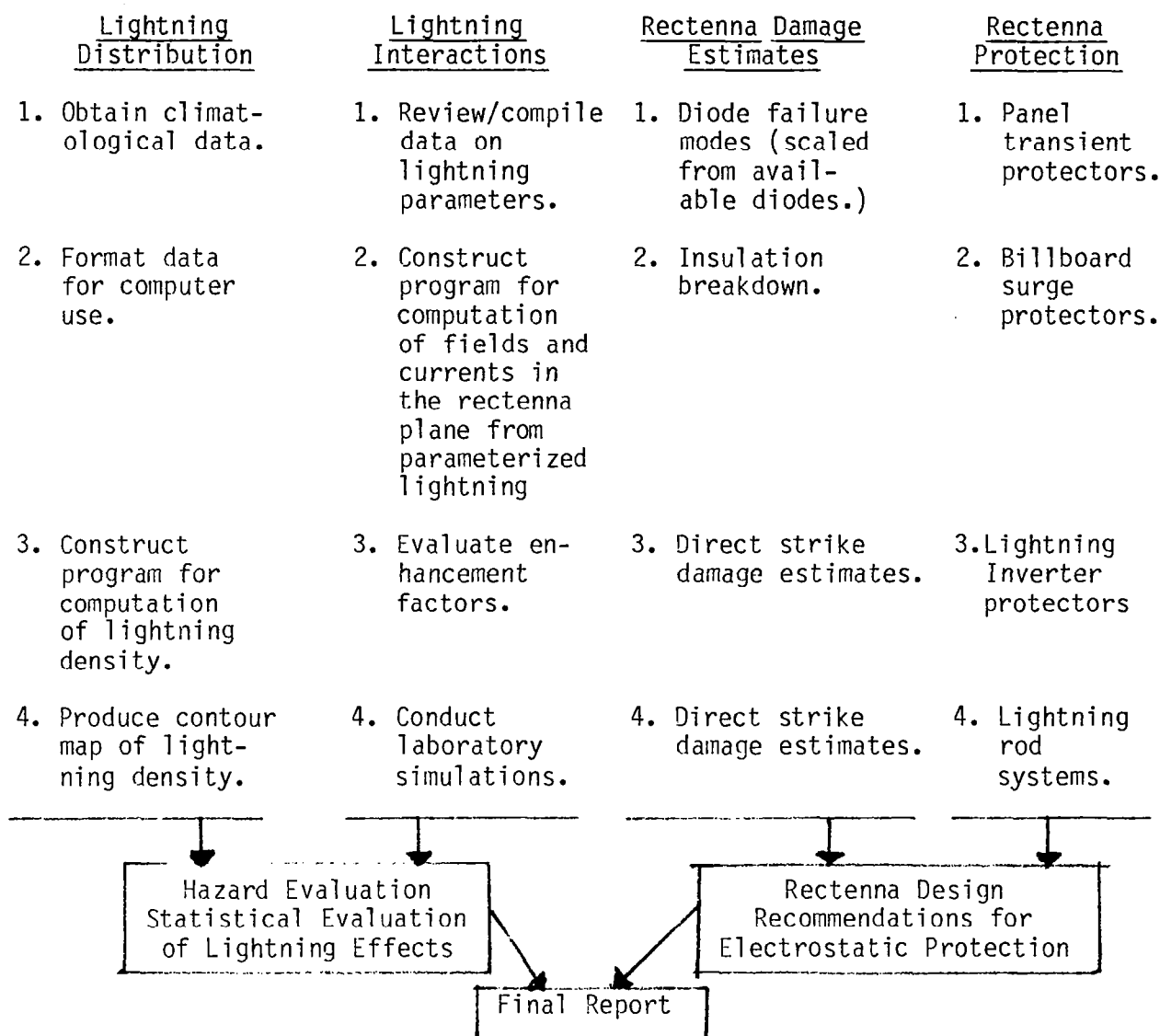
PREFACE

The objectives of this study are to evaluate the hazard posed by lightning flashes to ground on the SPS rectenna and to make recommendations for a lightning protection system that will provide sufficient protection to the rectenna. For purposes of this study, the SPS rectenna design is based upon the data supplied to us by Rockwell International in July, 1978.

This study has four major components, each with several elements of investigation. The components were: lightning distribution; lightning interactions; rectenna damage estimates; rectenna protection. The elements of each component are listed in Table A. The study plan was to proceed from top to bottom evaluating the elements listed in each component; work proceeded in a parallel manner for the four components. The organization of this final report reverses this order by presenting the more important results of the study first, then following this with the material and considerations leading to the conclusions.

TABLE A

Rectenna Electrostatic Protection



The Principal Investigator was J.W. Freeman, Jr., and the principal author of this section of the final report was A.A. Few, Jr. They wish to express their thanks and appreciation to the following co-authors, all of whom were or are associated with Rice University.

J. Bohannon
R.C. Haymes
D. O'Gwynn
M.F. Stewart

I. ANALYSIS OF LIGHTNING ROD PROTECTION CAPABILITIES FOR A CONFIGURATION SUITABLE TO THE RECTENNA

1. Cone of Protection Considerations:

I. 1.1 Definition and Considerations

The capability of a vertical conductor to attract a lightning flash is described by the cone-of-protection, or perhaps more accurately the cone-of-attraction. In theory, any lightning flash that would have entered this cone had the vertical conductor not been in place, will strike instead the conductor and be shunted to the ground. The method by which this process takes place is as follows:

The lightning stepped leader creates high voltages over a wide area on the rectenna because of the large charge on the leader tip. At points on the rectenna where the electric field reaches breakdown values due to local enhancement factors, upward propagating sparks are initiated which move to meet the downward propagating stepped leader. The upward propagating spark which first makes contact with the leader completes the electrical circuit and the lightning flash current will pass through the structure that initiated the successful upward going spark.

The cone of protection is primarily a function of the height of the vertical conductor because of the field-enhancement factor which enables the taller object to initiate the upward spark before lower objects. Other factors enter into the consideration of the cone of protection, such as the charge on the leader tip and the velocity of the leader, because these factors strongly influence the timing of the production of upward sparks and the height at which the spark and leader meet. In general, the results of research into this subject have shown that the larger the leader charge, then the larger the angle β of the associated cone of protection. Since larger leader charges are usually associated with the larger lightning currents, we find a fortunate result that the cone of protection increases with the potential hazard of the lightning flash.

It follows then that the angle β of the cone of protection (See Figure 2) varies with the particular lightning flash. $\beta = 45^\circ$ is a very commonly used design angle in the United States and many of the examples in this report employ $\beta = 45^\circ$.

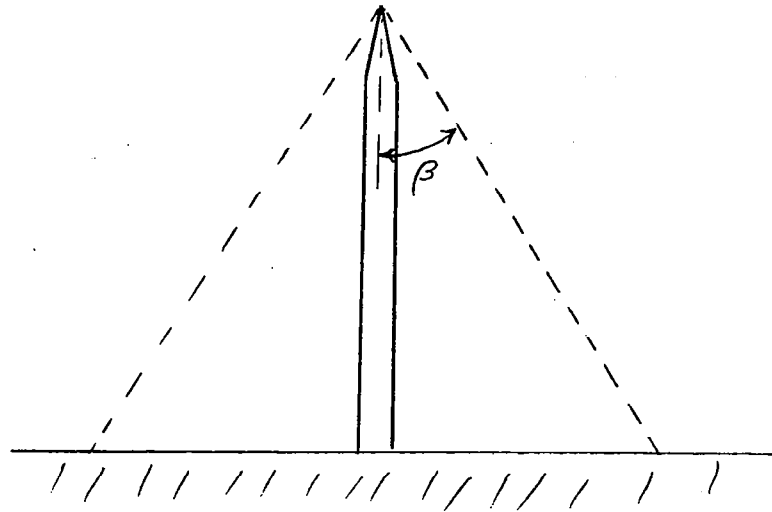


Figure 2

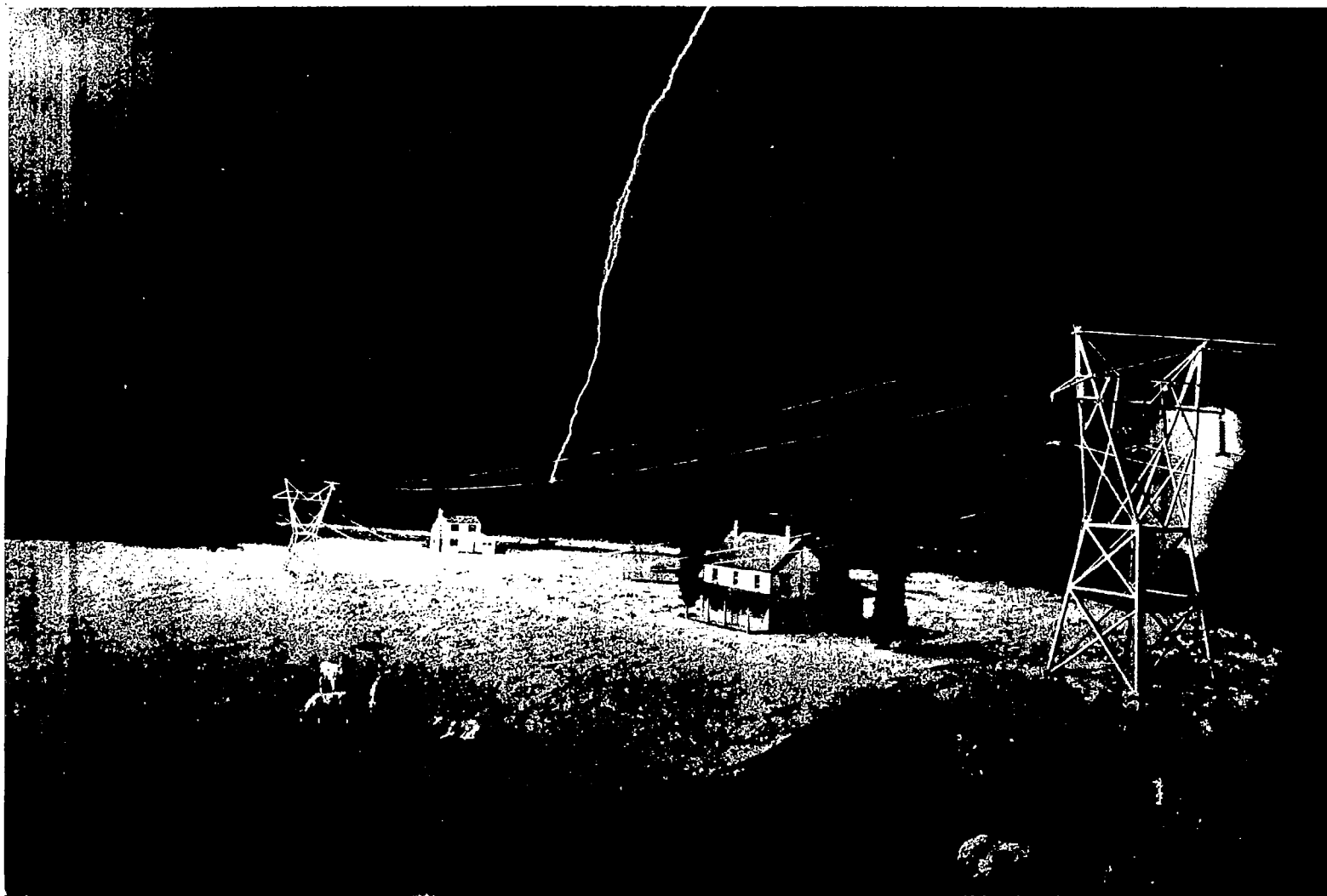
1.2 Distributed Lightning Protection Systems

The cone of protection and the experimental data used to evaluate are specifically related to the single elevated point, and in most cases the system under consideration is 10 to 100 meters in height. As will be seen later, lightning protection of the rectenna falls into a class of structures that requires distributed lightning protection tactics. Figure 3 illustrates a distributed system used by power transmission companies. The main point is that the cone of protection concept is of limited usefulness in the total protection problem. We will use it on the panel and billboard scale as a technique to make a comparative assessment of capabilities of various configurations.

2. Lightning Rod Protection Configurations Compatible with the SPS Rectenna

We have considered three different configurations of lightning rod systems in this effort. In the smallest scale system considered each rectenna panel (0.74m in width) had a short lightning rod attached; see upper example in Figure 4. In the medium scale system each rectenna support structure (14.69m apart) or billboard will have an attached lightning rod; see middle example in Figure 4. And, in the distributed protection system, short terminals located on each rectenna support structure (14.69m apart) were connected by horizontal conducting structures; see lower example in Figure 4.

As seen in the analysis of the billboard scale system, it is impractical to seriously consider larger scale systems.



POWER LINES EMPLOY DISTRIBUTED LIGHTNING PROTECTION SYSTEMS. THIS ILLUSTRATION SHOWS A "STATIC" OR GROUNDED PROTECTION WIRE TAKING A STRIKE AND PROTECTING THE POWER LINES BELOW.

FIGURE 3

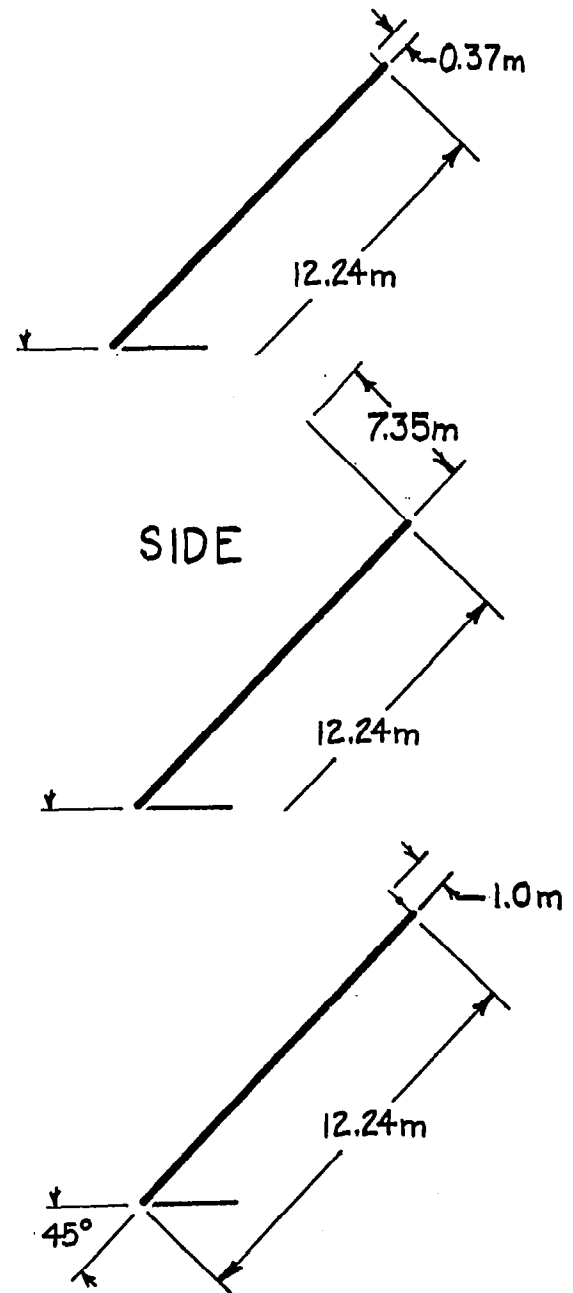
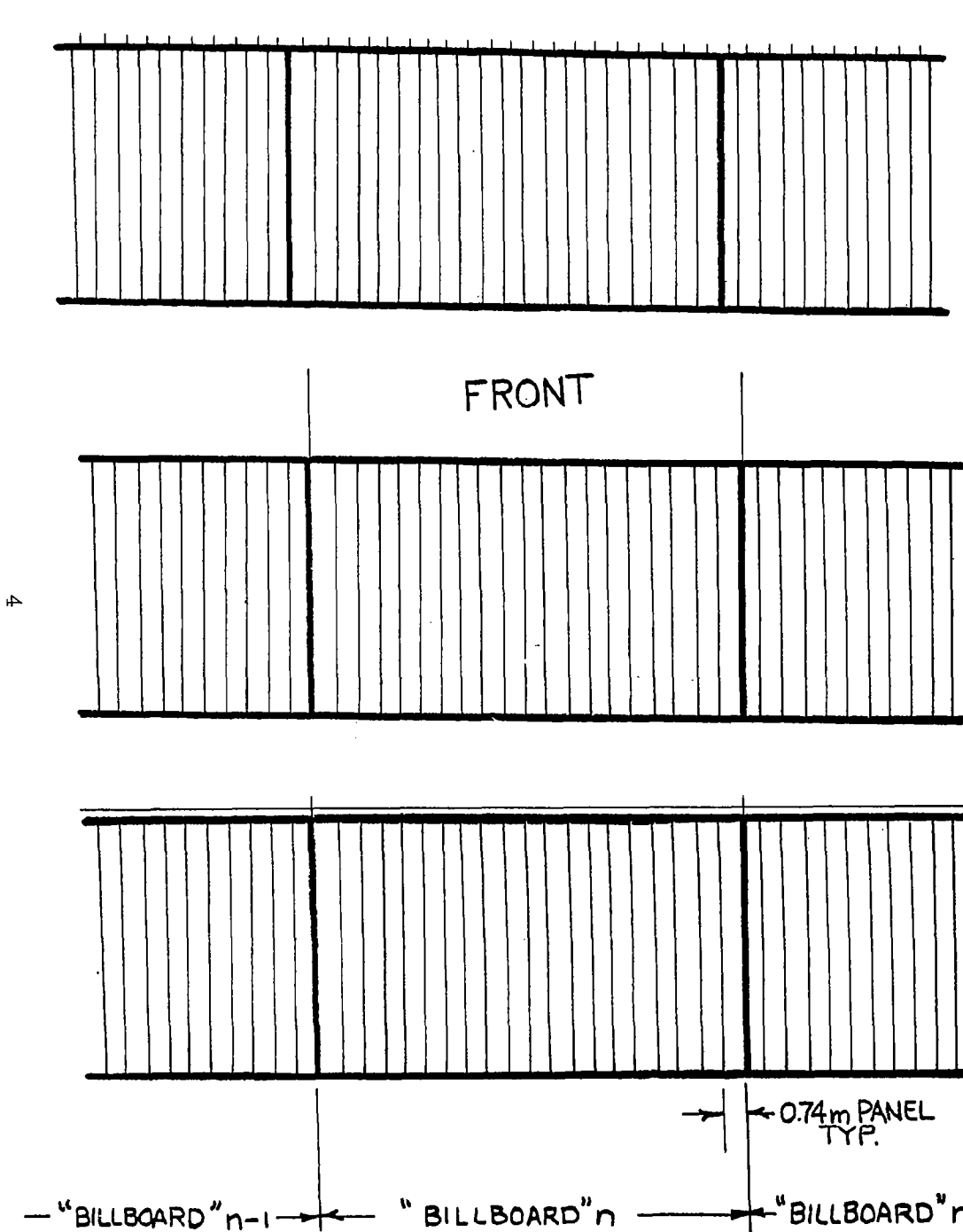
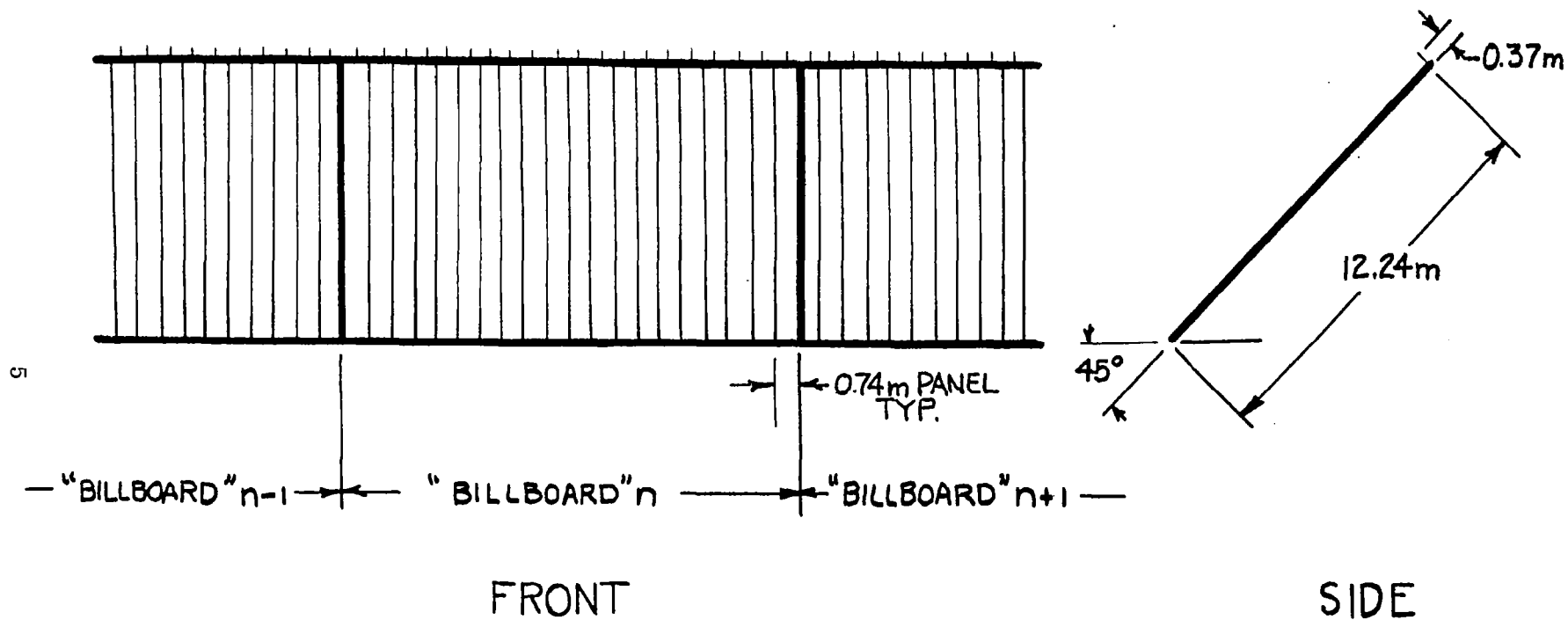


FIGURE 4



PANEL SCALE LIGHTNING PROTECTION SYSTEM

FIGURE 5

2.1 Lightning Rod Protection at the Panel Scale

In this system configuration a relatively short lightning rod is positioned at the top of each panel and oriented perpendicular to the panel face (see Figure 5). Conceptually the rod is centered on the top of the panel, but in practice it could be on the panel edge without altering the results of this analysis.

Let α be the inclination of the rectenna. Figure 6 illustrates the case where β , the angle of the cone of protection, is greater than α . This figure applies only to the conditions in the vertical plane that passes through the lightning rod and is perpendicular to the rectenna face. In this particular projection it appears that the short (example 0.74m) lightning rod on the panel provides adequate protection to the rectenna. In other projections we see that there are, however, "holes in the armor."

Figure 7 is an enlargement (x10) of the lightning rod portion of Figure 6, and defines the parameters to be used in the following discussions. The cone of protection intersects the plane of the rectenna to form conic sections:

- (1) If $\alpha + \beta = 90^\circ$ the intersection is a parabola.
- (2) If $\alpha + \beta < 90^\circ$ the intersection is an ellipse.
(this is the case illustrated in Figures 6 & 7)
- (3) If $\alpha + \beta > 90^\circ$ the intersection is a hyperbola.

If we now look at the intersection of the cone of protection with the panel for the specific cases above, we see the emergence of the protection problem with this type of lightning rod protection configuration. From the geometry of Figure 7 we see that the axis of the cone is at $l = L \tan \alpha$ and that the vertex of the conic is at $d = L \tan (\beta - \alpha)$ relative to the top of the panel.

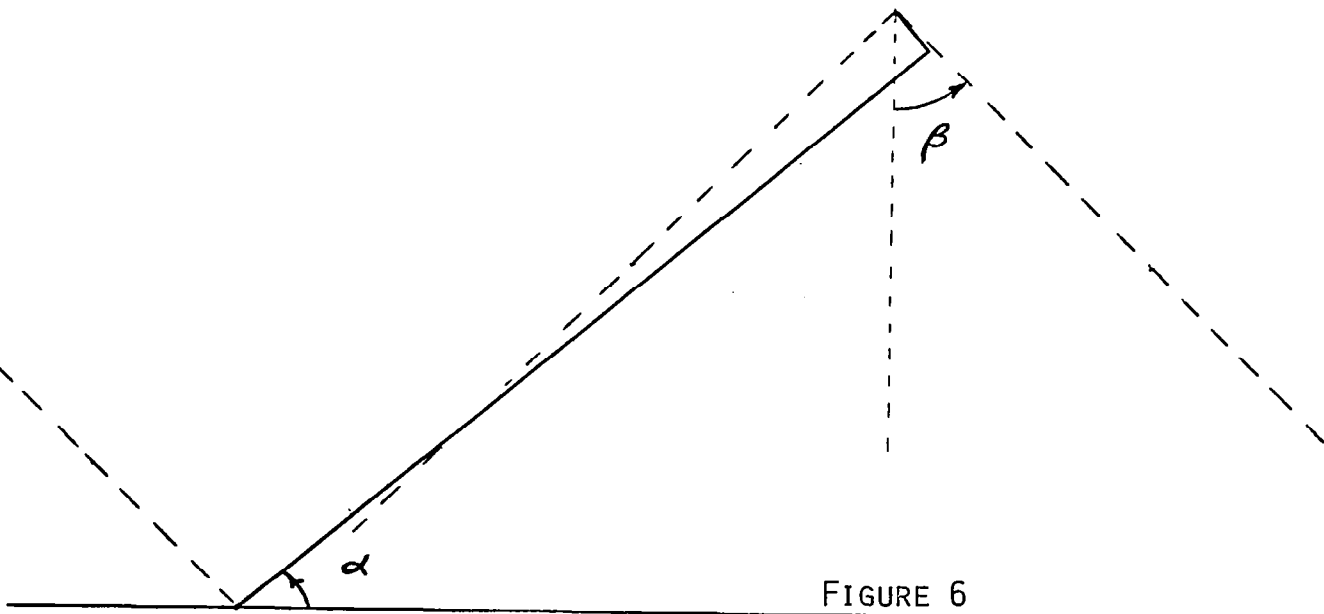


FIGURE 6

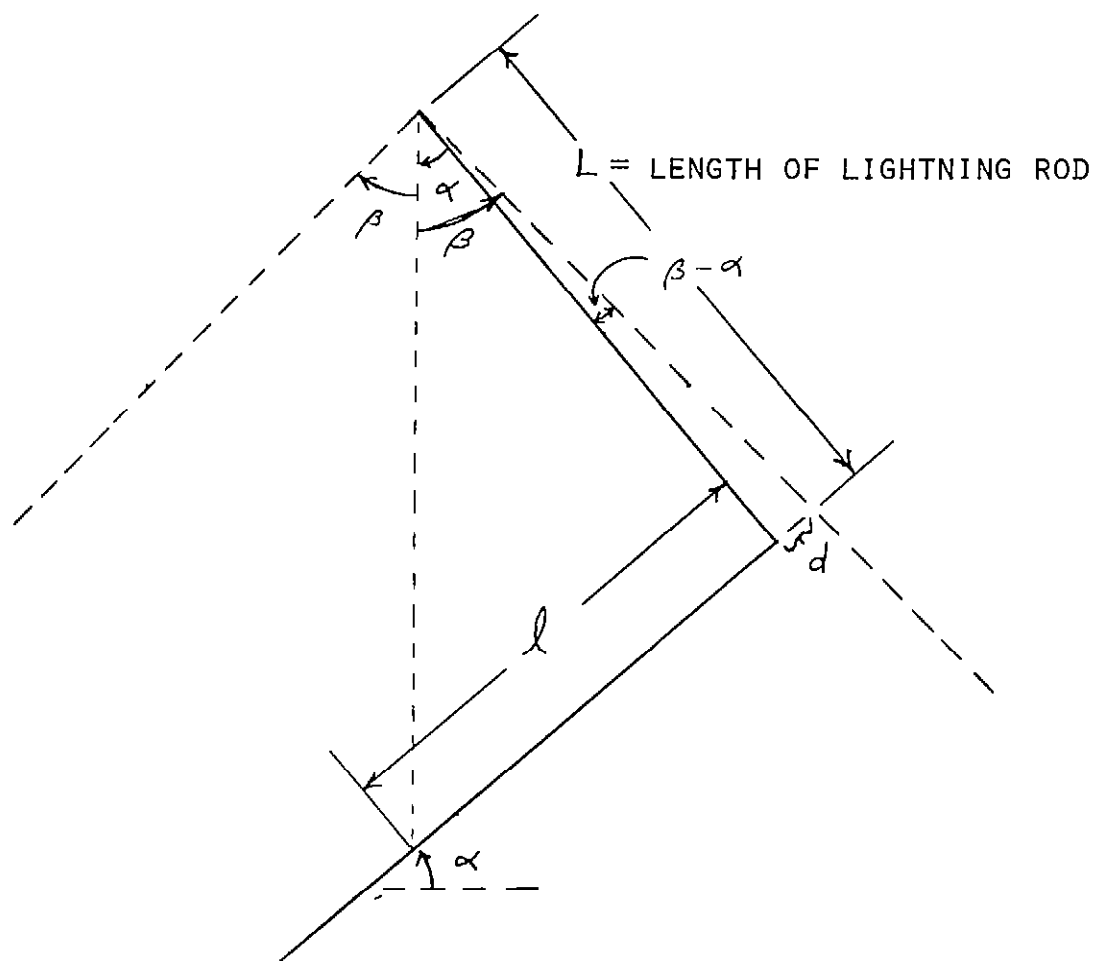


FIGURE 7

ENLARGED VIEW OF THE UPPER END OF THE
RECTENNA IN FIGURE 7.

In a coordinate system defined in the rectenna plane with the origin at the axis of the cone and the y axis directed north (toward top of rectenna) and the x axis directed east, the equation for conic is:

$$\frac{x^2 \cos^2 \alpha}{L^2 \tan^2 \beta} + \frac{y^2 (\cos^2 \alpha - \sin^2 \alpha \tan^2 \beta) \cos^2 \alpha}{L^2 \tan^2 \beta} + \frac{2y \sin \alpha \cos \alpha}{L} = 1$$

For the parabolic solution this equation reduces to:

$$x^2 = - \frac{2L \sin^2 \beta}{\cos \beta \cos \alpha} \left(y - \frac{L}{2 \cos \beta \cos \alpha} \right)$$

In figure 8 we have plotted the intersection of cones of protection for three lightning rods of lengths 0.185m (= 1/4 panel width), 0.37m (= 1/2 panel width), and 0.74m (= panel width.)

In these examples the rectenna inclination angle α is taken to be 45° and the cone of protection β is equal to 45° . The resulting intersections are parabolas for the cases depicted in Figure 8. For the parabolic solution the cone of protection is parallel to the face of the rectenna in the vertical plane bisecting the panel (The view of Figure 6 and 7 except that here $\alpha = \beta = 45^\circ$).

At lower latitude sites (below 40°) the rectenna inclination angle α is less than 45° and the 45° cone of protection intersection becomes an ellipse; in Figure 6 the vertical projection illustrates the intersection in the plane through the lightning rod. The elliptic solutions leave regions along the base of the rectenna unprotected. Hence, the parabolic solutions of Figure 8 and the table (Fig. 9) represent maximum protection capabilities of the cone of protection with the panel scale protection configuration. The small ellipse in Figure 11 shows the cone of protection intersection for $\alpha = 40^\circ$, $\beta = 45^\circ$, and $L = 0.74\text{m}$.

2.2 Lightning Rod Protection at the Bay or Billboard Scale

In this system a longer lightning rod is placed at the center (or end) of each bay or billboard making them 14.69m apart. The mathematical description here is identical to that for the panel scale system (2.1). Only sizes are different. Figure 10 illustrates the billboard scale system.

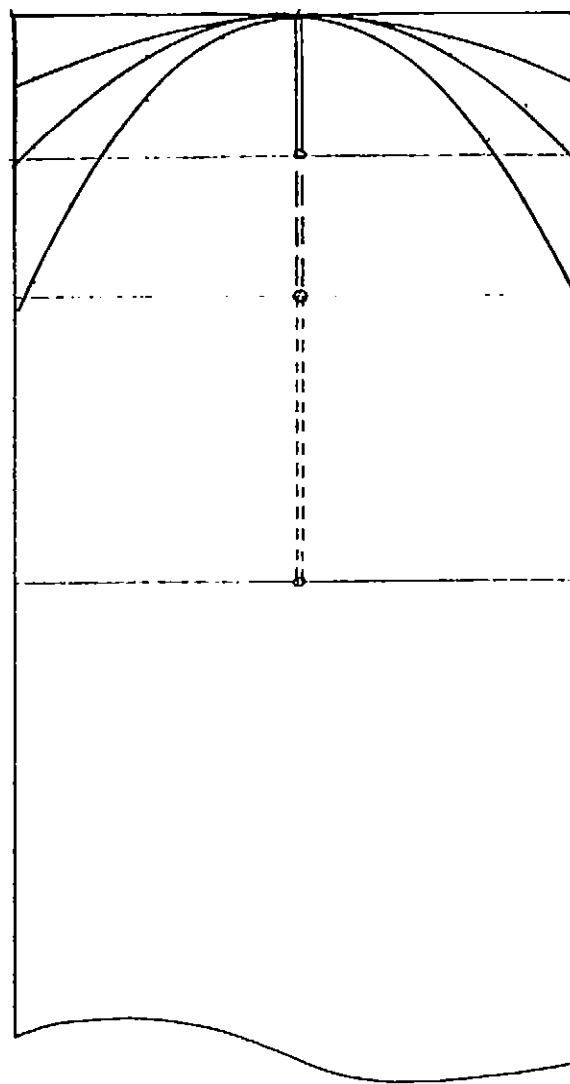


FIGURE 8

THE INTERSECTION OF THE CONE OF PROTECTION WITH A RECTENNA PANEL (THE CURVED LINES) SHOWN IN THE PLANE OF THE PANEL. LIGHTNING ROD LENGTHS = $\frac{1}{4}$, $\frac{1}{2}$ AND 1 TIMES THE PANEL WIDTH ARE SHOWN PROJECTED VERTICALLY ONTO THE PANEL.

PARABOLIC TYPE SOLUTIONS

<u>ROD LENGTH IN METERS</u>	<u>UNPROTECTED AREA IN %</u>	<u>UNPROTECTED AREA X ENHANCEMENT FACTOR</u>
.185	1.1%	2.9%
.37	.55%	1.5%
.74	.28%	.74%

FIGURE 9

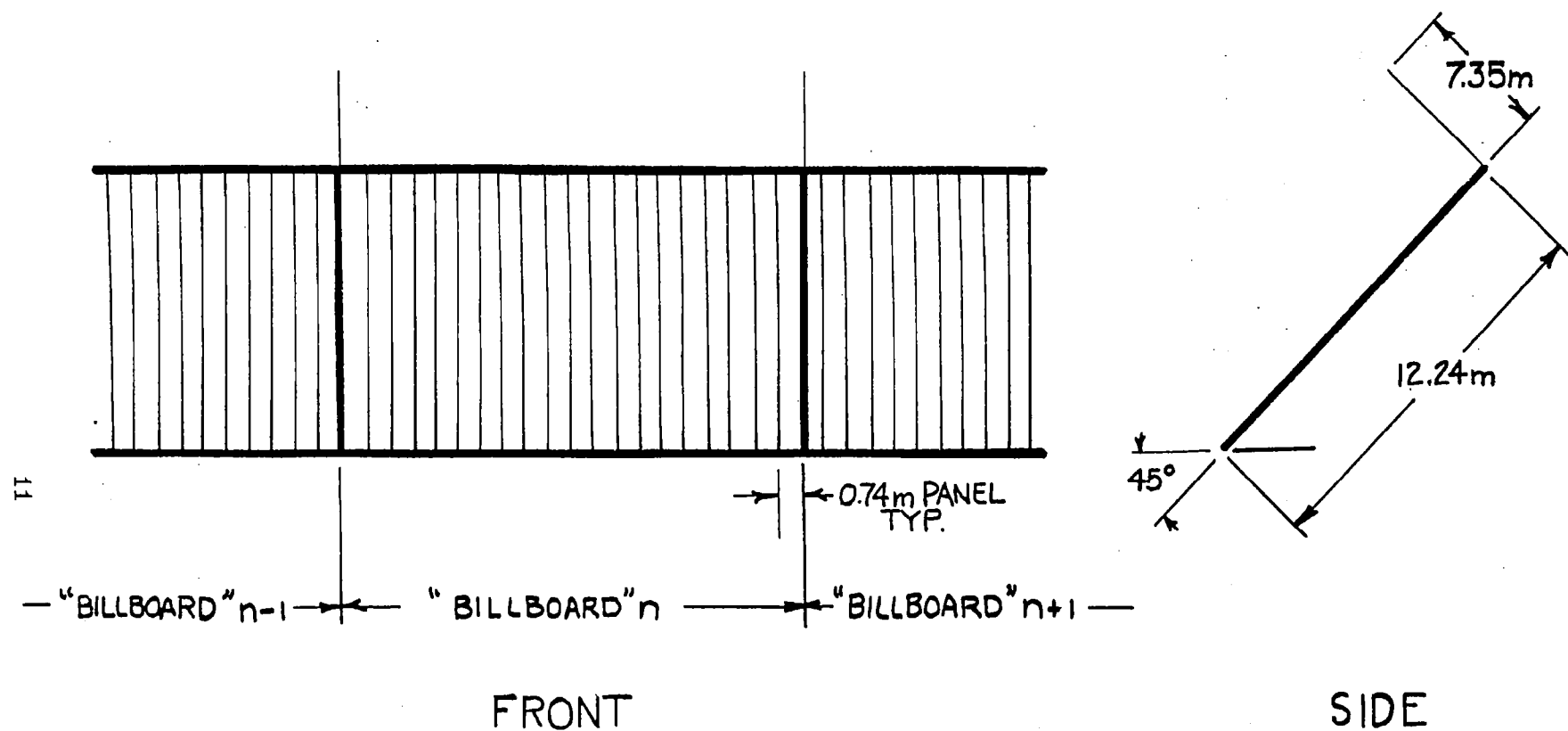


FIGURE 10

BILLBOARD SCALE LIGHTNING PROTECTION SYSTEM

To illustrate the cone of protection concept for this configuration we use as an example, $\alpha = 40^\circ$, $\beta = 45^\circ$, and $L = 7.35\text{m}$ ($= 1/2$ billboard width). The resulting intersection is a portion of an ellipse and is shown on Figure 12. Even if these long (7.35m) lightning rods were placed every 14.69m, a significant fraction of the rectenna (6.7% or when weighted by enhancement factor 18%) is unprotected (i.e. is not inside a cone of protection).

Furthermore, there are serious mechanical problems associated with supporting these long (i.e., over 22 feet) lightning rods. We think these examples are sufficient to demonstrate that configurations employing fewer lightning rods at longer spacing decreases protection and creates structural problems that ultimately will increase the total materials requirement.

For example, if we were to increase the length of the lightning rod in this configuration to the point that it could offer protection to the billboard in front of the one on which it is mounted (i.e. to the south), then with the appropriate phasing of rods between rows of billboards we could get total protection in the cone of protection context. The length of the rods would need to be 12m in order to provide this coverage.

2.3 The Distributed Lightning Protection System

The distributed lightning protection approach replaces the many lightning rods with a continuous horizontal conducting structure, as depicted in Figure 13. The region of protection now becomes the volume beneath two planes whose intersection is the horizontal protecting structure. This protection tactic is essentially the one employed by the power transmission companies. The angle between the protecting planes and vertical is variable; 45° is thought to be adequate but some designs use 30° for extra protection. This line is called the "static" by the power companies and this term is used here for convenience.

Figures 7 and 8 provide the correct geometric considerations for the distributed lightning protection if we interpret the end point of the lightning rod to be the location of the static. We note that the figures apply anywhere along the rectenna, not just in the specific locations required by the lightning rod analysis.

For consistent comparisons with the other lightning rod systems we will use $\alpha = 45^\circ$. Since $\alpha < 45^\circ$ for rectennas below 40° latitude, the top edge of the rectenna is protected by the static for any value of L , the displacement distance. If we try to use a smaller, more conservative value for β , we will run into problems in protecting the top edge of the rectenna with any system that does not cast a radio shadow on an active rectenna surface. The design constraint that we will use to specify L will be that the southward plane of protection intersect the rectenna surface at the base. Therefore,

$$L = 12.2\text{m} \tan (45^\circ - \alpha).$$

For α in the range 45° to 30° , L has the range of values 0m to 3.3m. This simple analysis ignores the protecting capability of the immediate southward row of the rectenna on the base of the row being considered. When these additional protective effects are considered we find that:

$$L = 6.1m (1 - \tan \alpha)$$

For α in the range 45° to 30° , L now has the range 0m to 2.6m.

Figure 13 gives the configuration of the distributed lightning protection system for $\alpha = 30^\circ$, which represents the most difficult situation to protect. In this situation the static is displaced by 2.6 meters from the top edge of the rectenna; note that the 45° planes of protection provide total coverage of the rectenna.

We wish to emphasize that the set of horizontal statics not only provide total protection in the sense that lightning flashes are expected to hit the statics instead of the active rectenna surfaces but that this system also reduces the induced voltages and currents in the rectenna. We estimate that induced charges, currents, and potentials are reduced by 1/2 by the static protection system.

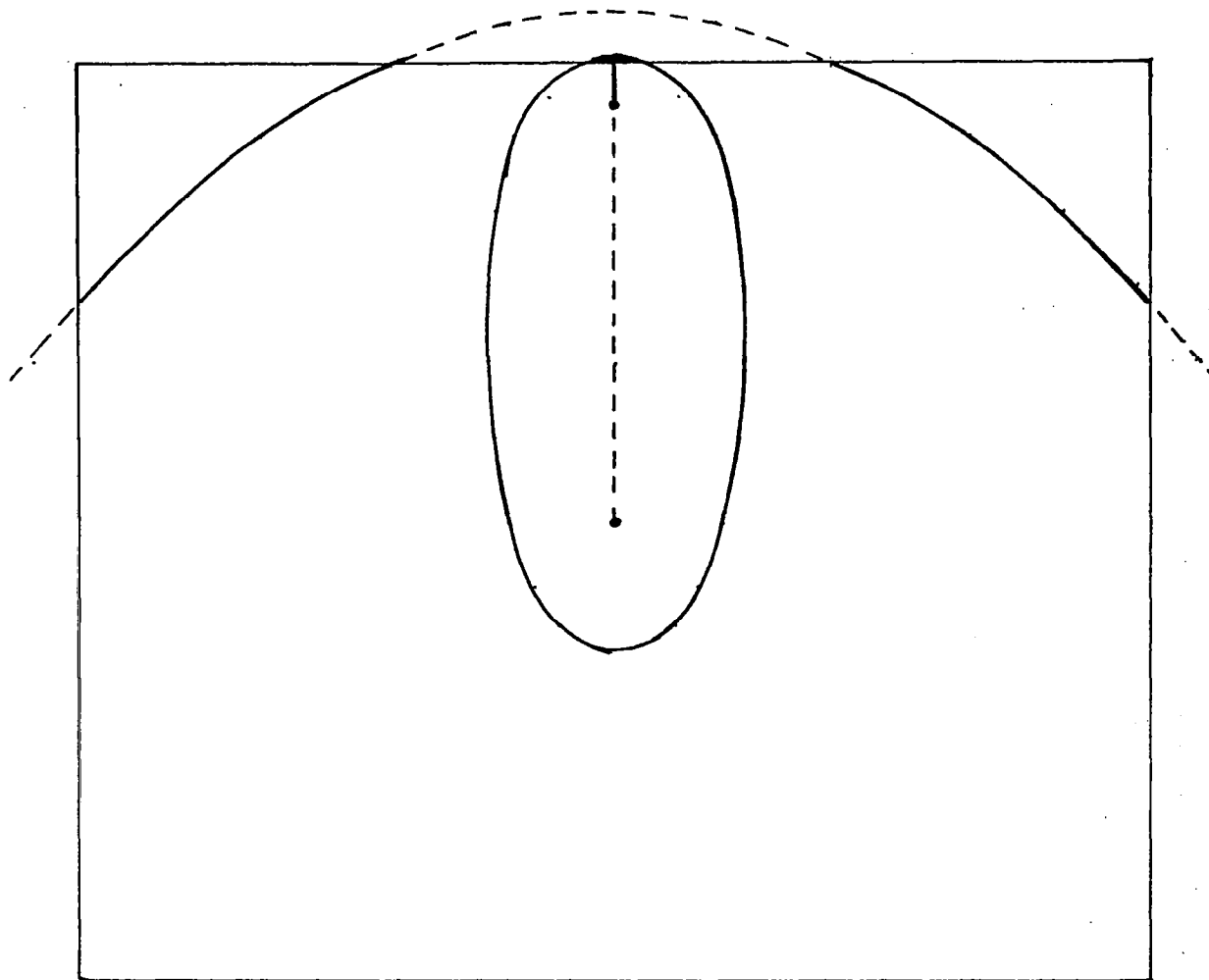


FIGURE 11

PANEL SCALE PROTECTION COMPARED TO BILLBOARD
SCALE PROTECTION SHOWN AS IN FIGURE 8 EXCEPT
HERE ON A BILLBOARD.

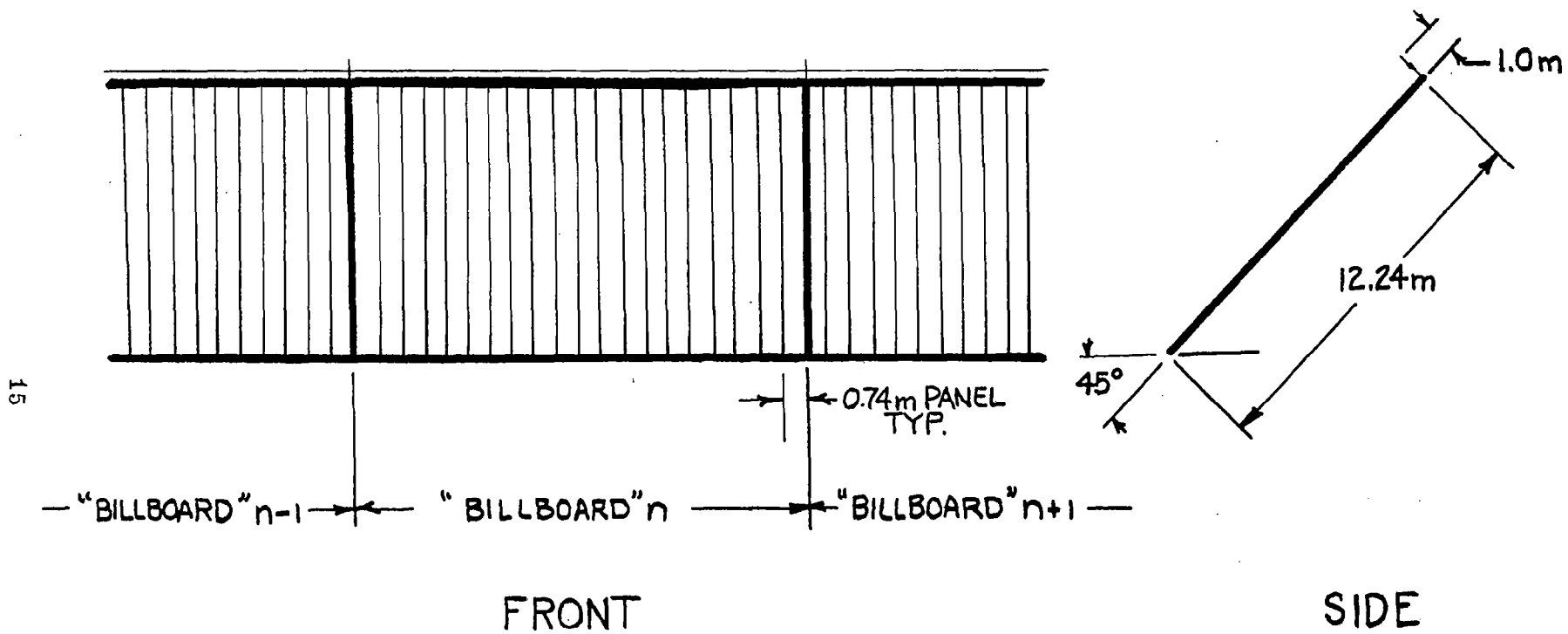


FIGURE 12

DISTRIBUTED LIGHTNING PROTECTION SYSTEM

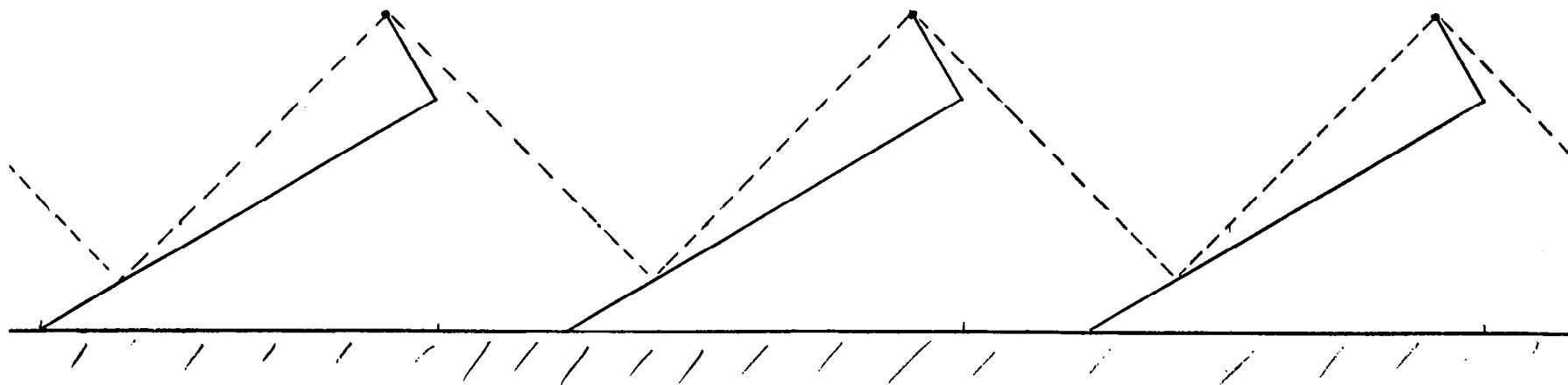


FIGURE 13

DISTRIBUTED LIGHTNING PROTECTION SYSTEM
ILLUSTRATING FORWARD AND BACKWARD PRO-
TECTION FOR SMALL INCLINATION ANGLES

II. SIMULATIONS OF LIGHTNING STRIKES TO THE SPS RECTENNA WITH AND WITHOUT PROTECTION

A series of experiments were performed in our electrostatic test chamber with a scale model of the SPS rectenna. The experiments consisted of exposing the model rectenna to a series of high voltage discharges produced with a Tesla coil.

The strikes to the rectenna were photographed using time exposures in a darkened room. A wire from the upper plate conducted the discharge to the vicinity of the model rectenna and provided us with a limited control over the area of the strike. This allowed us to keep the strikes near the volume in focus by the camera.

Different areas of the model rectenna were protected by different systems, and one area was unprotected. The following paragraphs describe samples of these experiments:

1. The Unprotected Rectenna

Most of the strikes were to the upper edge of the billboard because of the larger enhancement factor at that point. Several strikes to the billboard face occurred.

In Figure 14, we see two strikes to the unprotected billboard section, one of which is to the billboard face. Notice that these strikes are perpendicular to the face when near the face; we would anticipate this because the equipotential lines are nearly parallel to the face here.

In Figure 14, we also see for comparison the three lightning protection systems modeled. To the left is the billboard scale system; to the right is the panel scale system; and behind the flashes is the distributed lightning protection system.

2. The Panel-Scale Protection System

The next three figures are examples of strikes photographed on the section of the model rectenna that was protected by the panel-scale lightning protection system.

In Figure 15, we see two strikes on the same billboard, both of which terminate on the panel-scale lightning rods.

Figure 16 shows two strikes from a different view going to two different billboards. The panel-scale protection system here is seen to protect only the front billboard. Protection is probably greater for real lightning because in our experiments we artificially bring the "leader tip" very close to the billboard with the wire.

Multiple strikes to the panel-scale protection system are seen in Figure 18. One of the strikes goes directly to the billboard face. this type of failure will occur in nature, but with lower probability than illustrated here.

3. The Billboard-Scale Lightning Protection System.

Two sets of experiments were made with the billboard-scale lightning protection system. The one illustrated in Figure 19 corresponds to rods of length 7.35m. (A second series of strikes were made with rods cut to one-half of this length, but these were photographed in color and are not suitable for this report.) Figure 19 illustrates the capability of these long rods to direct lightning to the desired point.

In Figure 20, we have a side view of a billboard-scale protector taking a strike and protecting the billboard-face. Figure 21 illustrates the "hole in the armor" of the billboard-scale lightning protection system. Two flashes strike the protection system, but a third strikes the billboards between two protectors, as predicted in Figure 12. With real lightning this is less likely to happen, but it can and will occur.

4. The Distributed Lightning Protection System.

The displacement distance of the static from the billboard was scaled from 0.74m to make it correspond to the height of the panel-scale protection system. Fewer failures-to-protect were observed with this system but they did occur. With real lightning, they would be even less likely to occur.

In Figure 22, we see two strikes to two different billboards from the side view. Figure 23 shows two strikes to the same billboards, which were provided with a distributed lightning protection system. One strike is to the terminal support rod at the billboard edge, which is the preferred point of strike. The other strike goes to the horizontal static line between the terminal support rods.

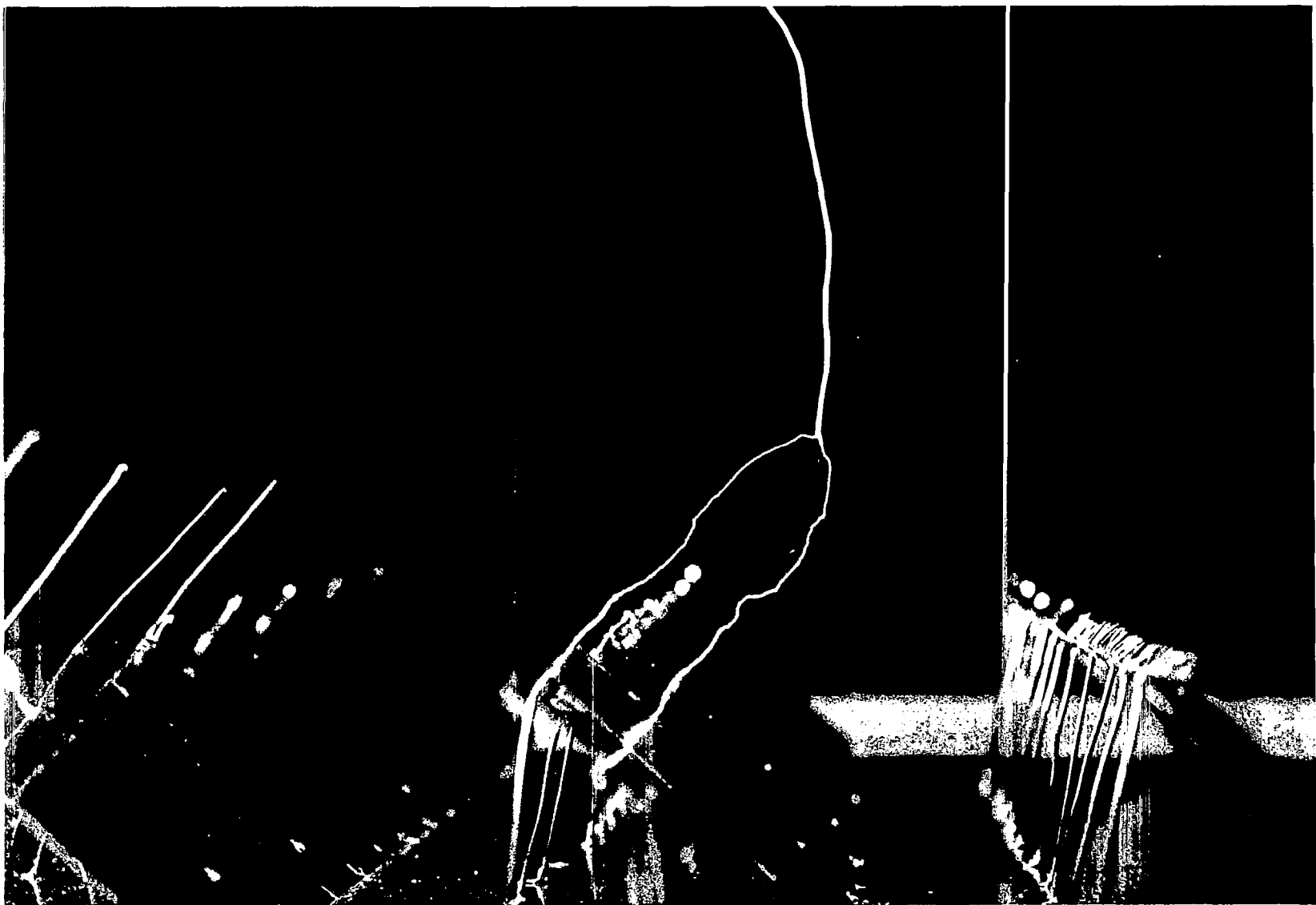


FIGURE 14

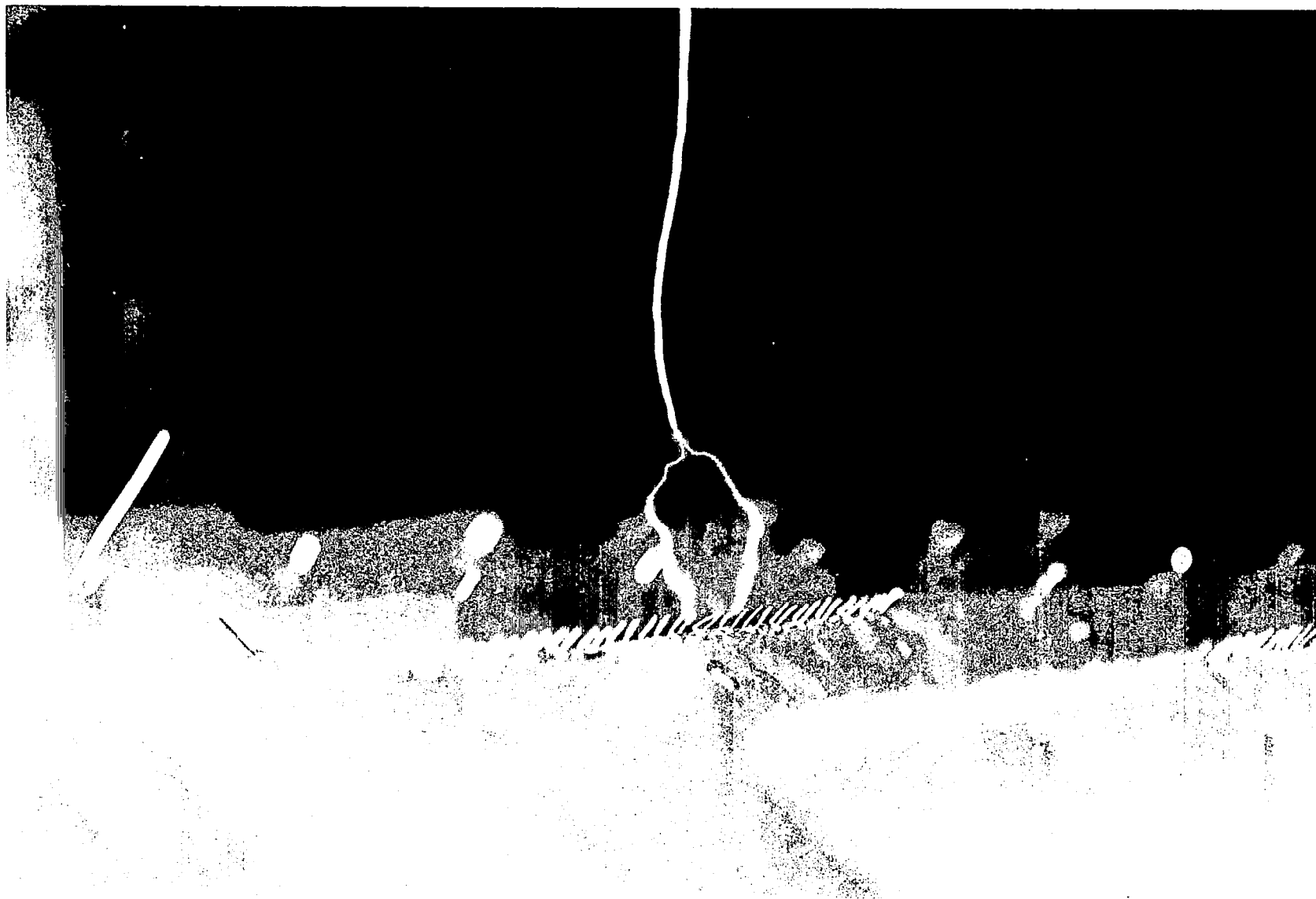


FIGURE 15

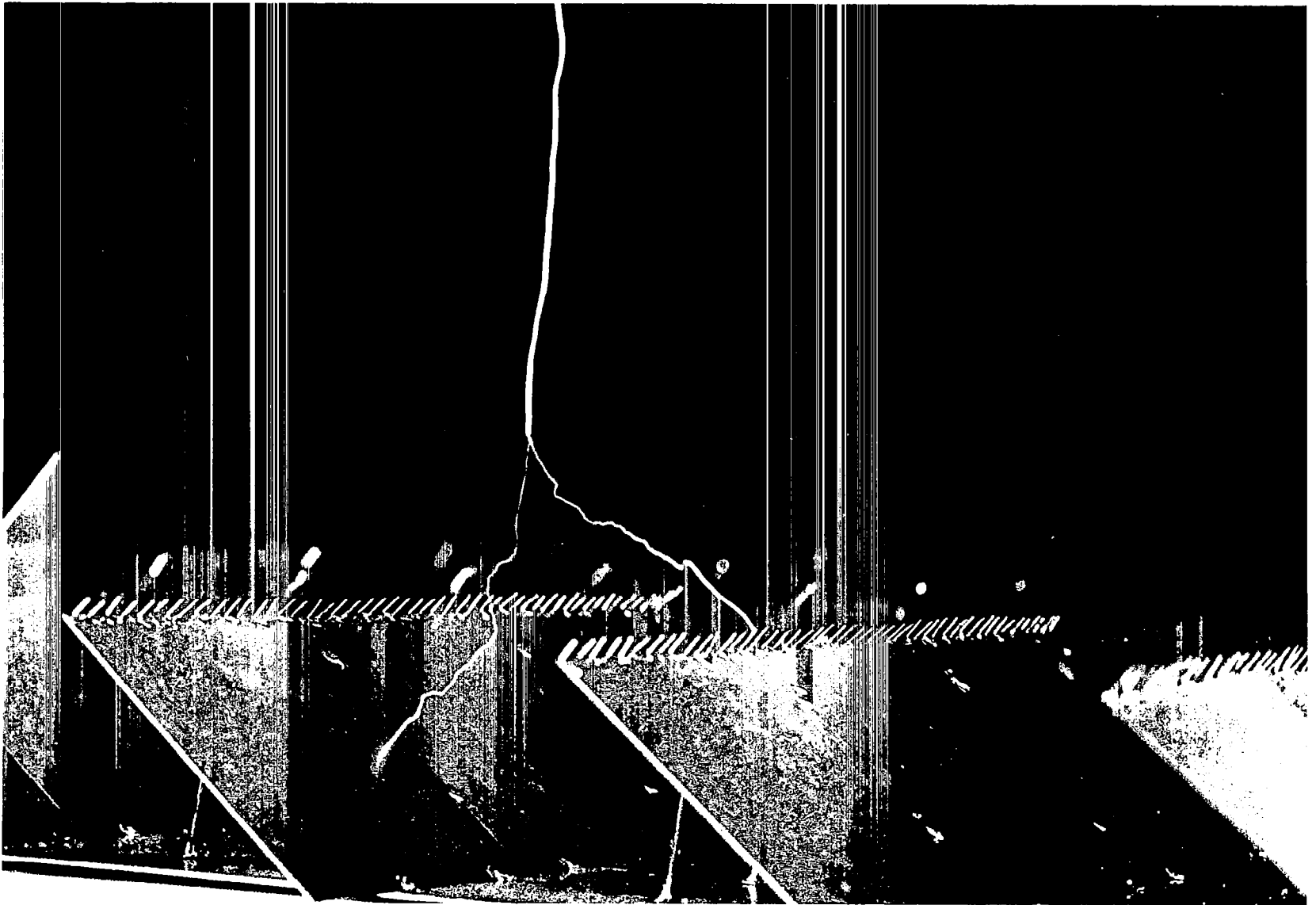


FIGURE 16

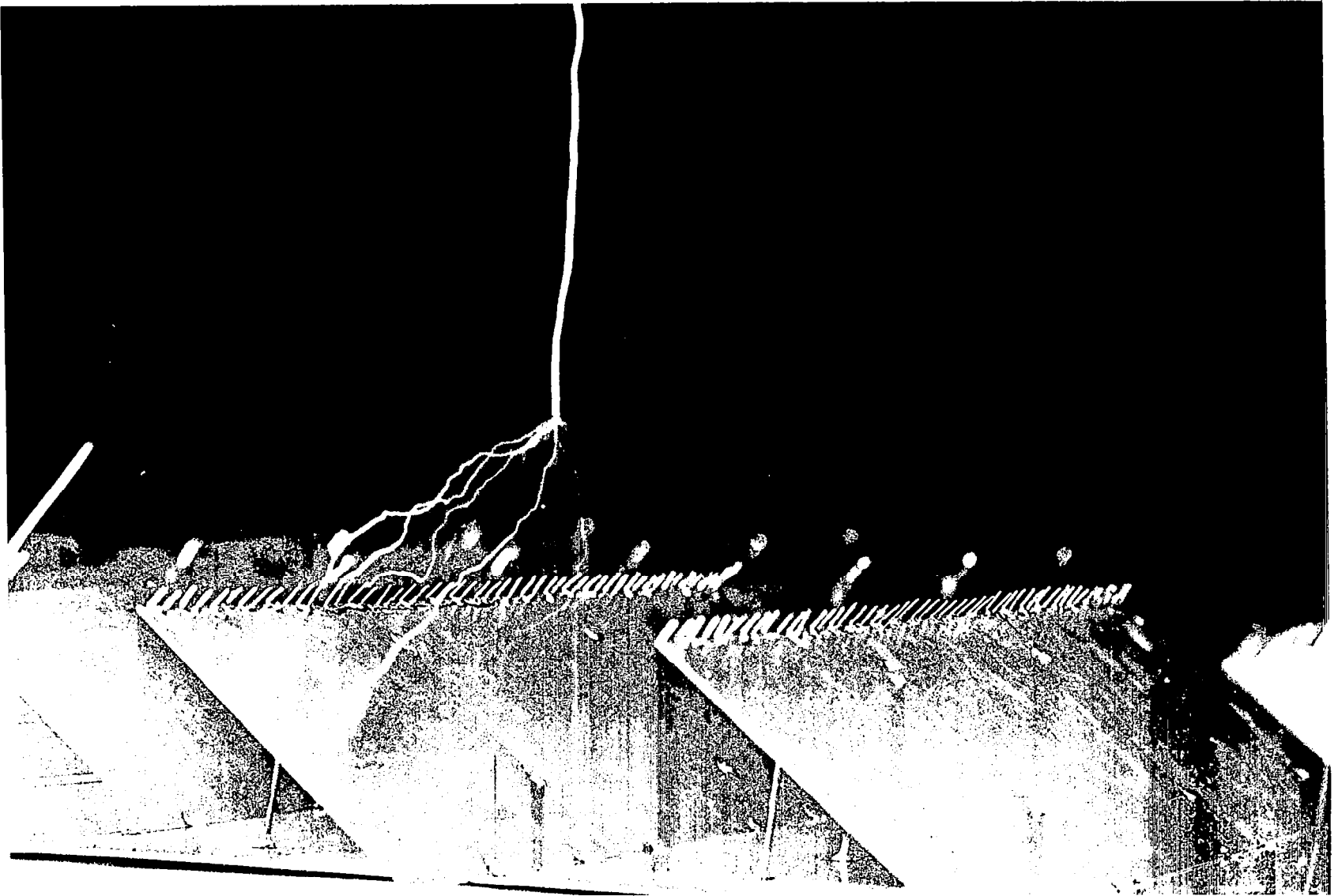


FIGURE 17

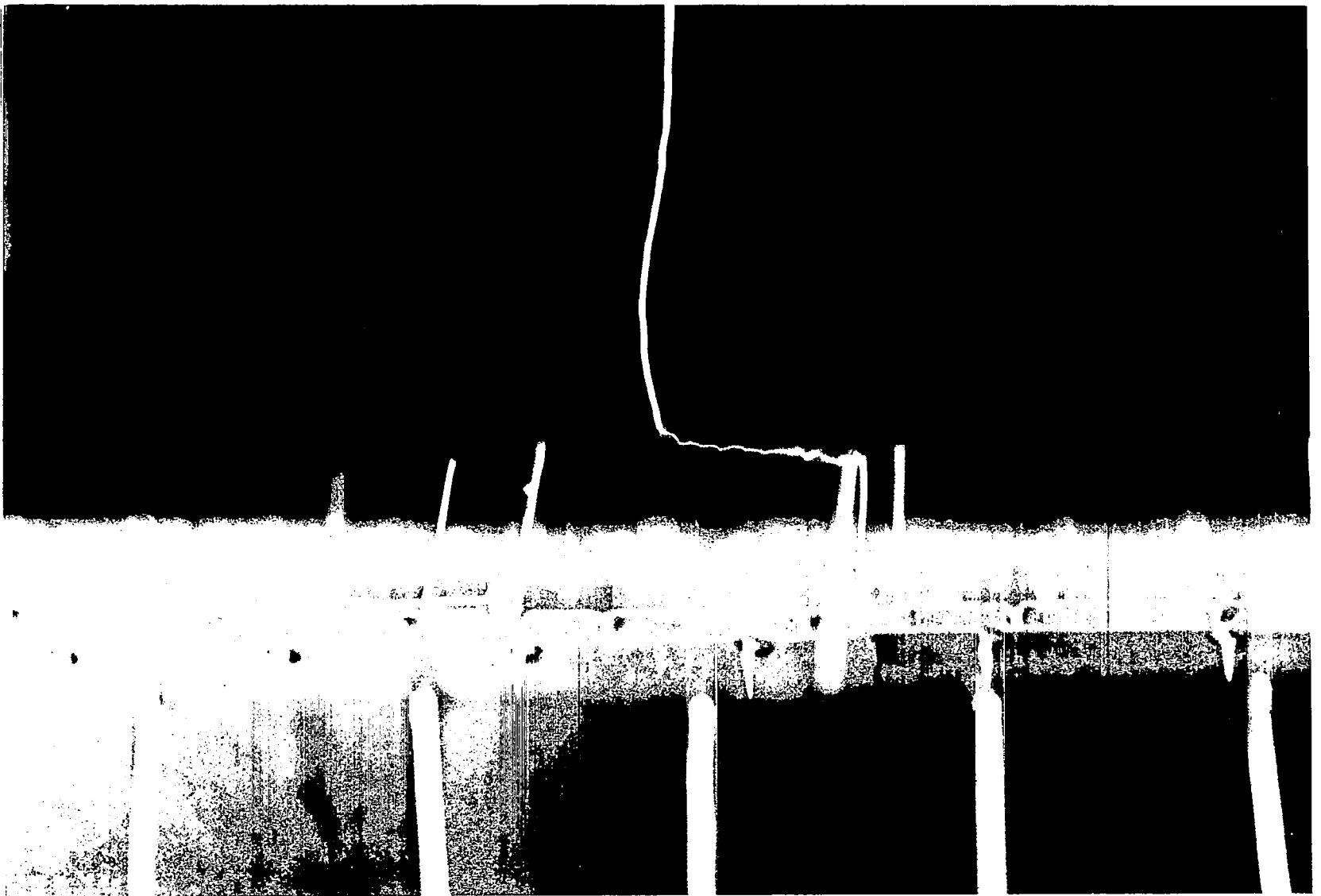


FIGURE 18

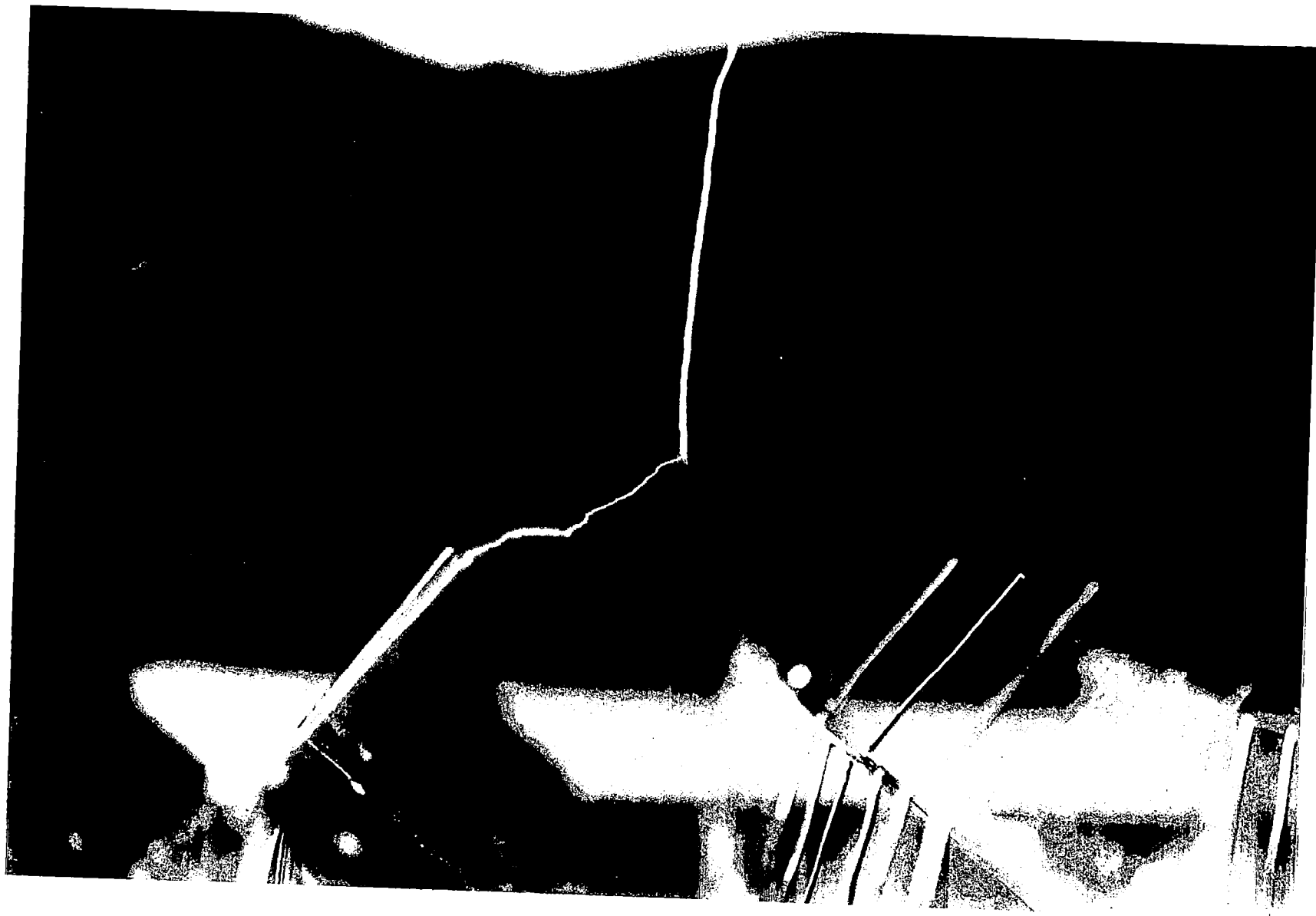


FIGURE 19

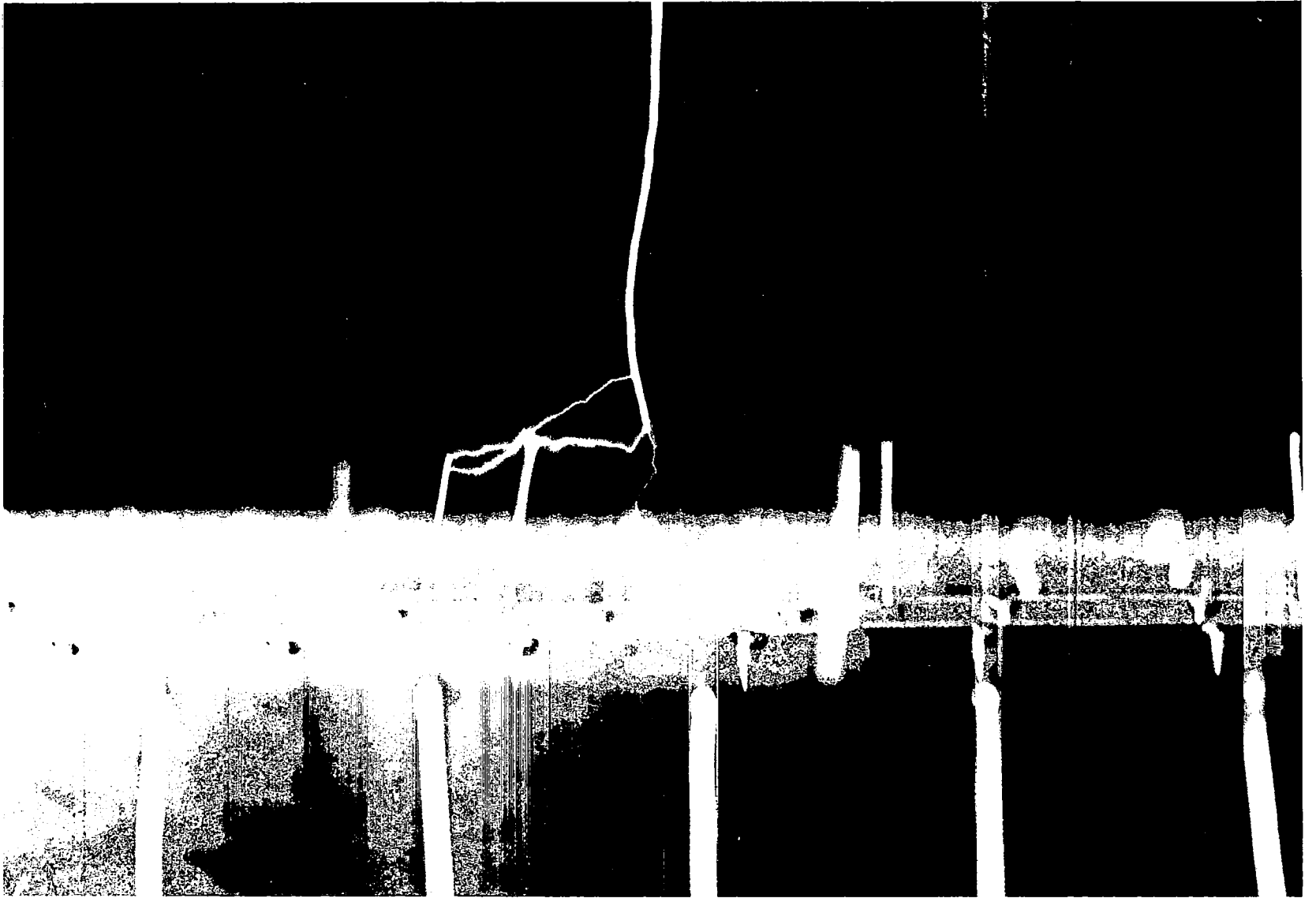


FIGURE 20

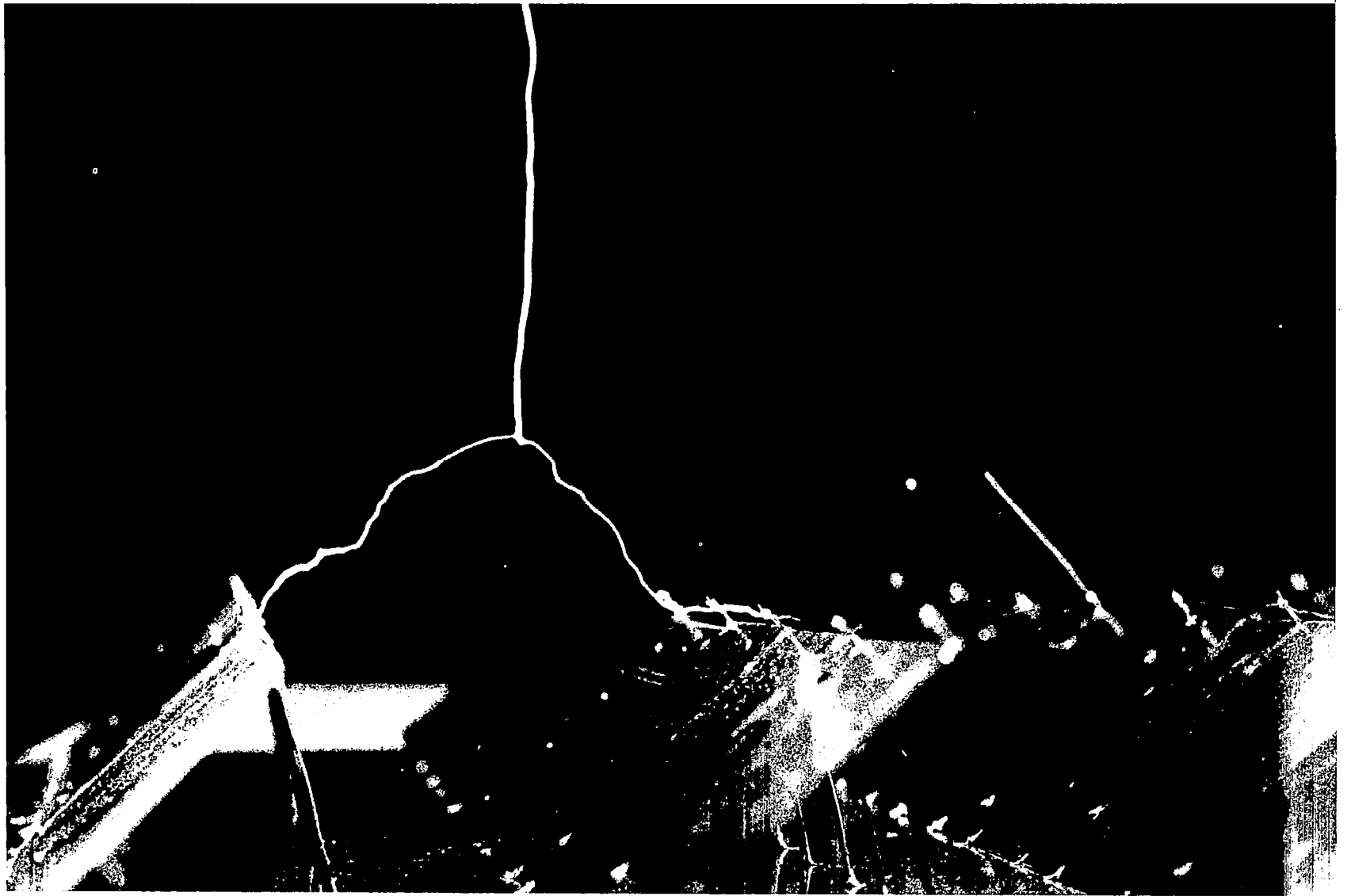


FIGURE 21

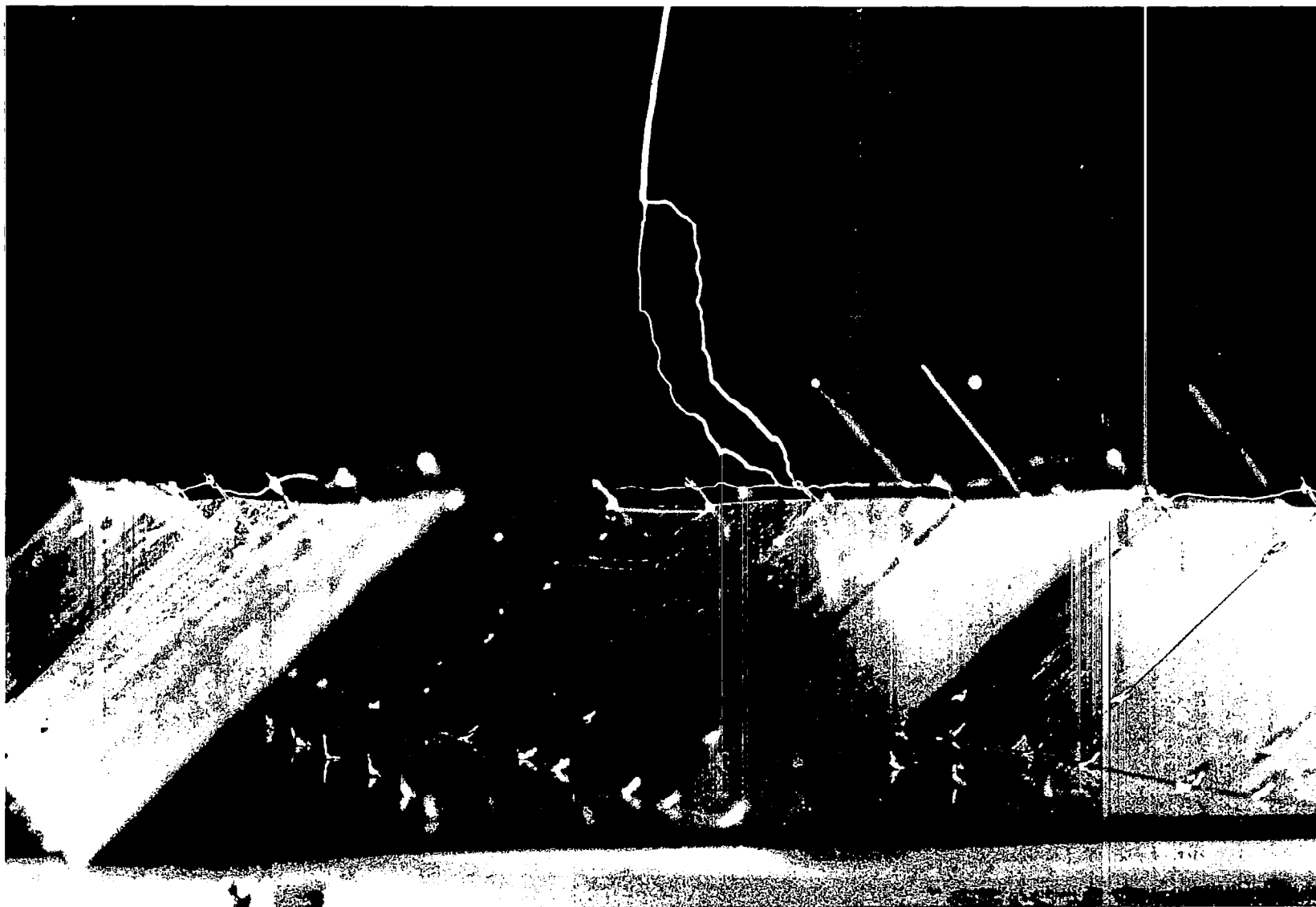


FIGURE 22

III. GROUNDING CONSIDERATIONS FOR THE PROPOSED LIGHTNING PROTECTION SYSTEM

The thundercloud charges induce a large surface charge on the rectenna below the cloud; during the stepped leader period even larger surface charges are induced on the region below the leader tip. Most of the current flowing during the return strokes of the lightning flash must be distributed by the grounding system to connect with the induced surface charges. If adequate paths for these currents are not planned and provided, the lightning will make its own paths. Most of the induced surface charge will reside on the horizontal statics of the recommended distributed lightning protection system. The primary grounding system described here is to provide low impedance paths for the redistribution of the induced surface charges and the part of the lightning charge that resides on the rectenna surface.

1. Primary East-West Grounding

It is absolutely necessary that the horizontal statics have a good low impedance connection at billboard edges. The static should appear to be a continuous very low impedance conductor in the east-west direction, as illustrated in Figure 24.

2. Primary North-South Grounding

It is also necessary that the statics are mutually grounded in the north-south directions; there are two methods of achieving this:

2.1 Periodic connections north-south at the level of the statics. If these north-south statics are aligned along the billboard edges, then there will be little power loss due to microwave shadows (See Figure 24.)

2.2 Interconnect grounding in the north-south direction at the surface or sub-surface level (see figure 25) can also be used, but this approach creates a higher impedance to north-south currents on the static system.

2.3 A surface level grounding network is required in addition to the primary static grounding network. The surface network must handle the redistribution of induced charges on the rectenna surfaces and power distribution systems and it provides a safe working environment at the surface level. East-west continuity with low impedance connections must be provided at the base of the rectenna support structures, and north-south continuity with low impedance connections as discussed in 2.2 and illustrated in Figure 25 must be provided. Figure 26 highlights the surface level grounding network.

2.4. Interconnections between the primary and surface grounding networks should be provided by the vertical conductors located at every billboard upper corner; these are the same structures on which are mounted the terminals and supports for the statics. The vertical interconnections are highlighted in Figure 27.

2.5 The ultimate or final component of the grounding system is the tie-in to Earth ground. At regular intervals in the rectenna a deep earth grounding rod must be driven into the soil to make good contact with a conducting soil for earth ground.

The organization of the earth grounding system should be along diagonals, as illustrated in Figure 28. Here we see that the placement of earth ground at every fourth billboard but on a diagonal produces a grid such that lightning striking the primary grounding network will never have to travel more than 30 meters along the east-west conductors before finding a ground, or 32 meters along the north-south conductors (for a rectenna with a 40° inclination angle).

THE PRIMARY GROUNDING SYSTEM AT THE STATIC LEVEL

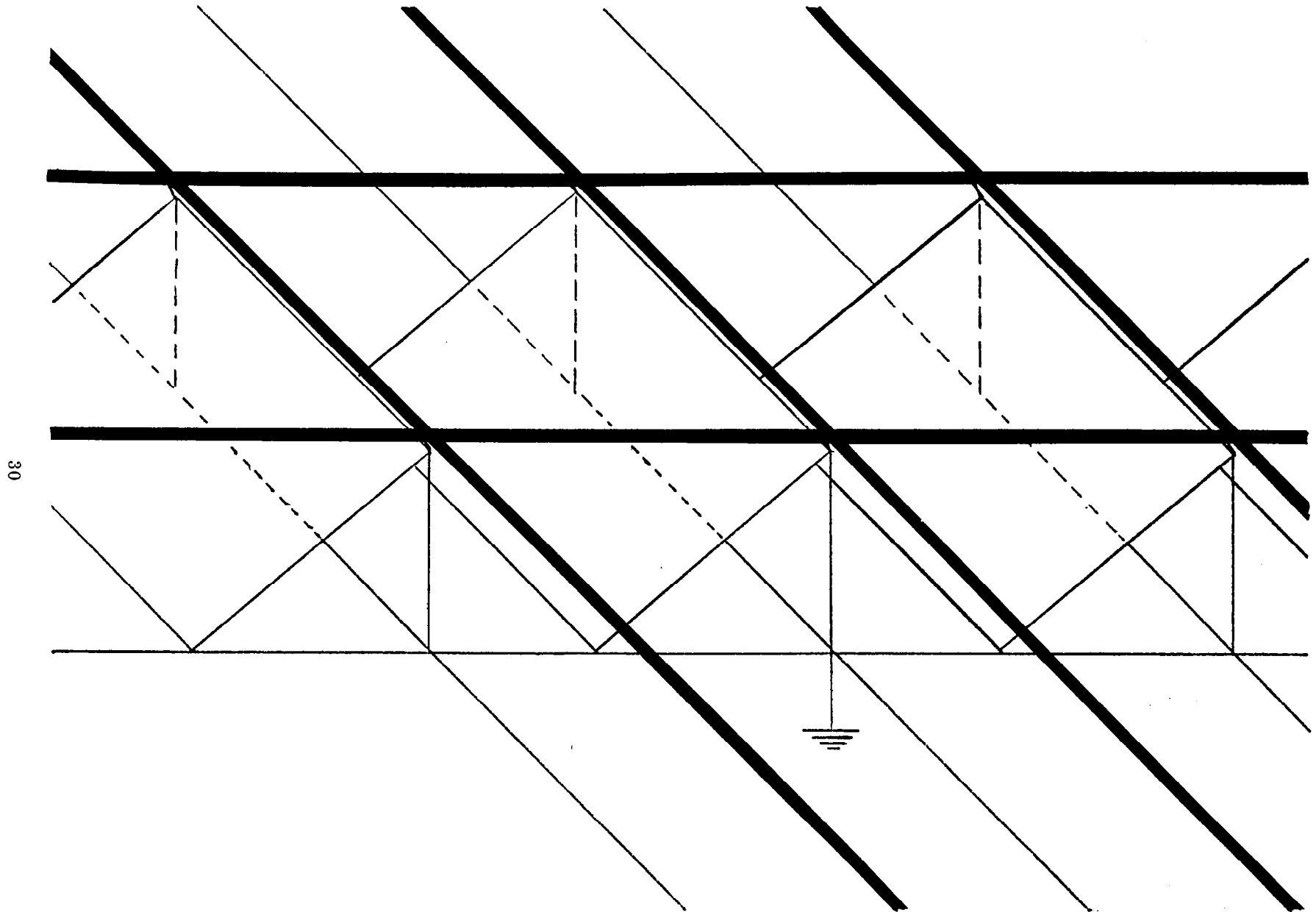


FIGURE 24

GROUNDING
RECTENNA LIGHTNING ROD SYSTEM

81

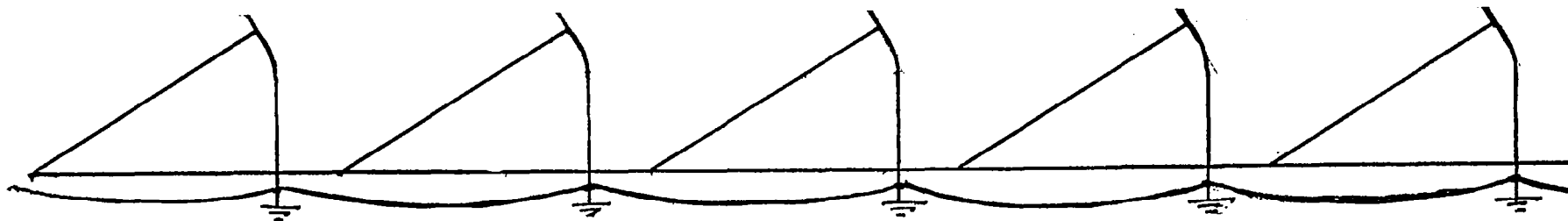


FIGURE 25

THE SURFACE-LEVEL GROUNDING NETWORK

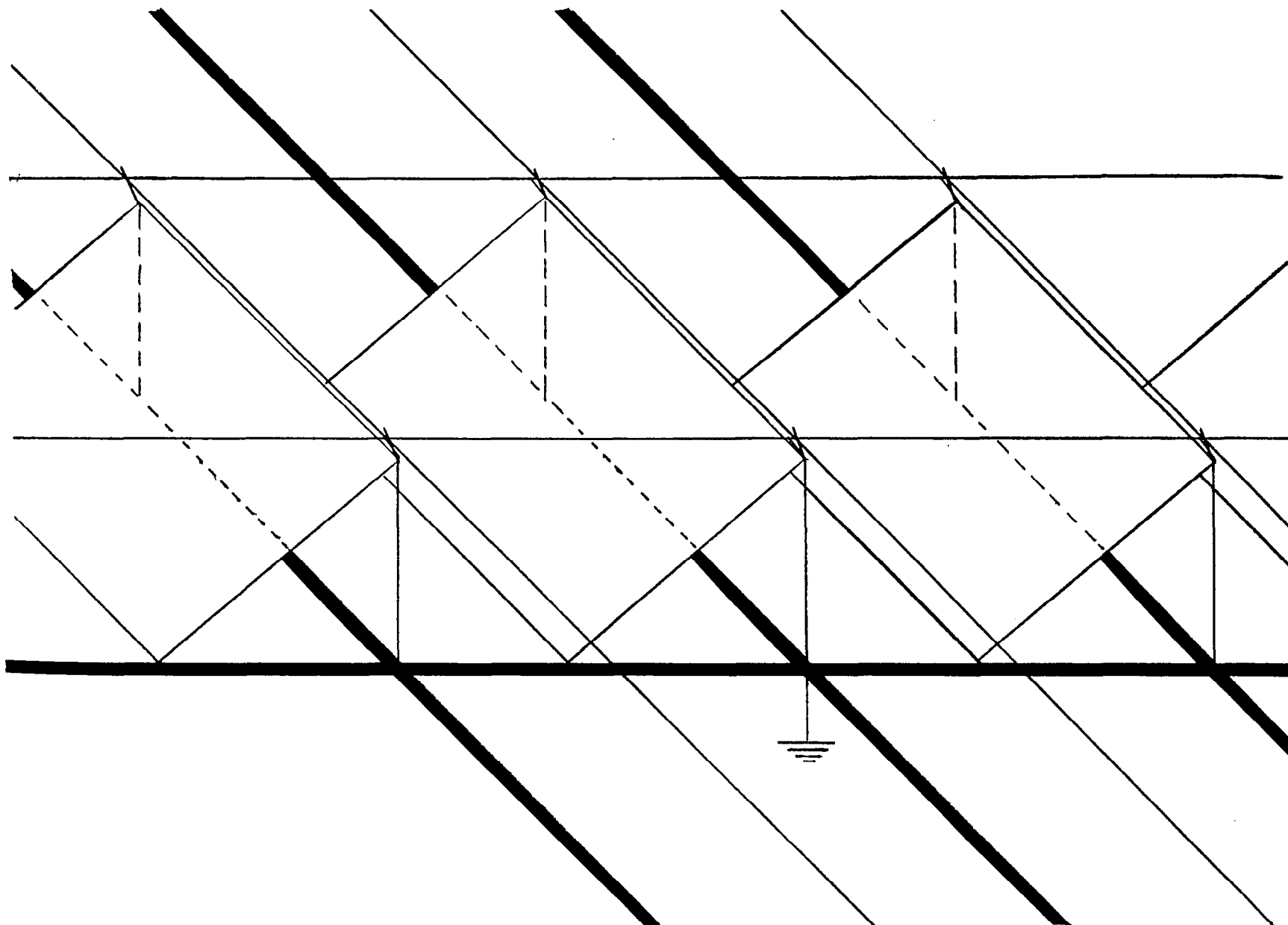


FIGURE 26

VERTICAL INTERCONNECTIONS BETWEEN PRIMARY
AND SURFACE NETWORKS AND ON EARTH GROUND

33

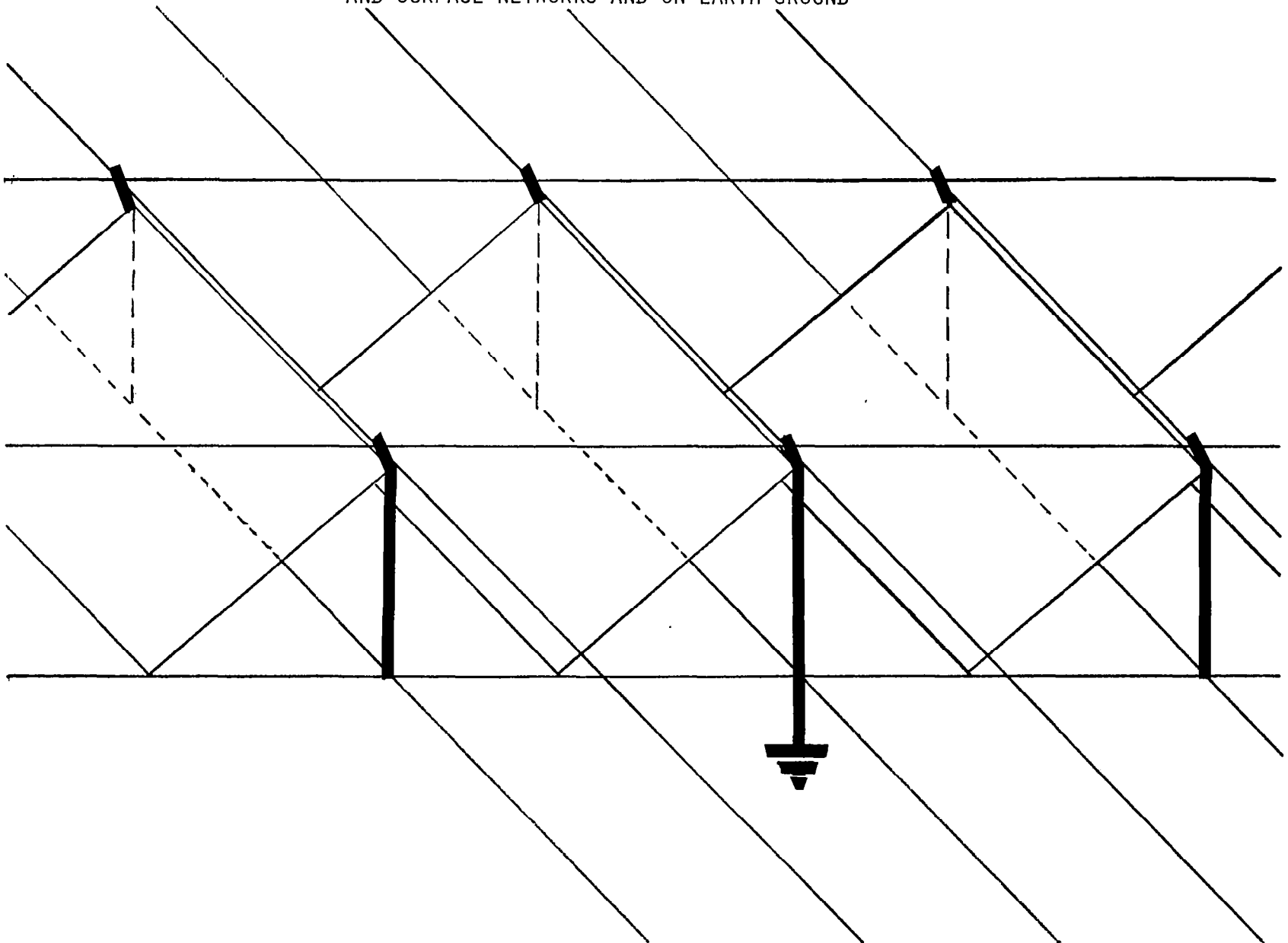


FIGURE 27

PLACEMENT OF EARTH GROUNDS

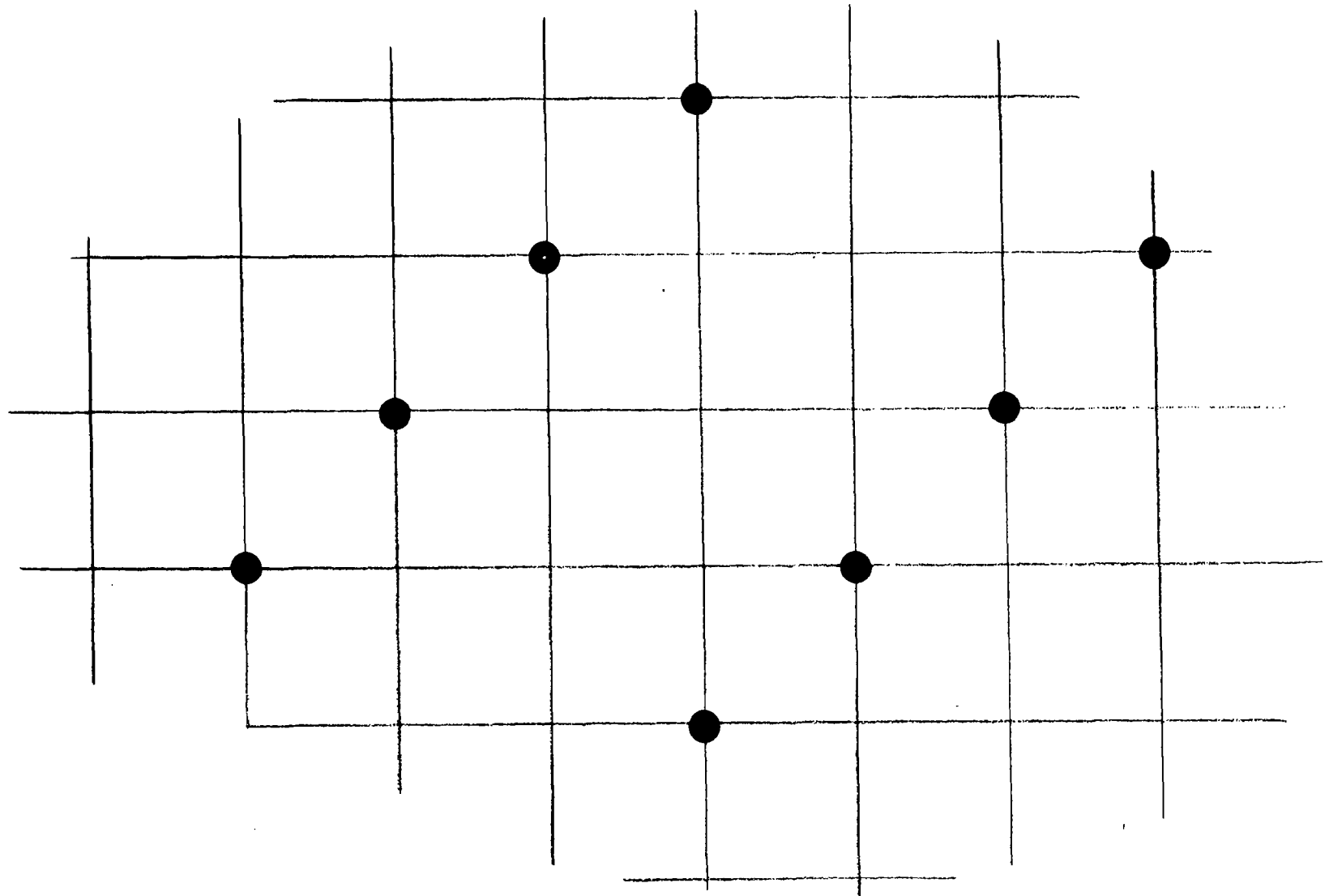


FIGURE 28

IV. MATERIALS AND SPECIFICATIONS FOR LIGHTNING PROTECTION

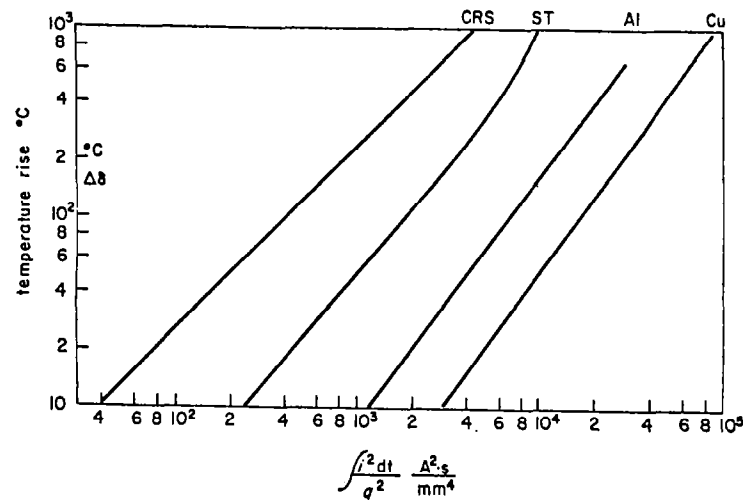
It is premature to specify the final form for the materials for the lightning protection system. We think that the system should be integrated into the structural design of the rectenna itself; in this case many other considerations are necessary in addition to the capability to conduct lightning currents. The data displayed in Figure 29 (H. Baatz, Protection of Structures, in Lightning Vol. 2, ed. by R.H. Golde) is useful for order-of-magnitude estimates of the lightning current requirements.

Example: If the design permits a 100°C temperature rise in an aluminum member carrying 10^5 Amps for 10^5 seconds, we need approximately 3 mm^2 cross-sectional area of aluminum material in the conductor. Note that the recommended cross-sections for building codes are larger ($\sim 80\text{ mm}^2$) indicating designs for lower temperature operation plus safety margins.

The lightning conductor need not be solid. From a structural point of view a tubular or other extruded shape would be preferable. Such configurations are compatible also with the lightning protection recommendations.

Specific values of materials for wire

Material	Steel	Copper	Aluminium
Density (g/cm ³)	7.7	8.92	2.7
Electrical resistance (Ω mm ⁻² m ⁻¹)	0.17	0.0178	0.029
Heat (cal °C ⁻¹ g ⁻¹)	0.115	0.093	0.023
Melting point (°C)	1,350	1,083	658



Temperature rise of conductors as function of current square impulse per cross-section square; Cu = copper, Al = aluminium, ST = steel, CRS = corrosion-resistant steel.

Cross-section for lightning conductors

Installation components	Material	Cross-section (mm²)	Dimension	
			Rod (mm, radius)	Strip (mm × mm)
Air termination Rods up to 0.5 m long	Steel, galvanized	50 (25) ^a	8	20 × 2.5
	Steel, stainless	110	12	30 × 3.5
Down conductors Conductors in ground	Copper	50 (16) ^a	8	20 × 2.5
	Aluminium ^b	80 (25) ^a	10	20 × 4
Sheet metal	{ Steel, galvanized Copper Aluminium, Zinc Lead			0.5 mm
				0.3 mm
				0.7 mm
				2.0 mm

^a Lowest cross-sections used in some countries.

^b Not for use below ground.

FIGURE 29

V. ESTIMATE OF POWER LOSS FROM THE BEAM

A rough maximum estimate of the power loss from the microwave beam due to the lightning protection devices can be obtained by assuming that the microwave shadow cast by the static lightning protection system is twice the crosssectional area of the devices. We assume that the conductors are 2 cm wide of 1 mm thickness tubular material, providing 60 mm² of crosssectional area for conducting. The assumed shadow of these structures is approximately 0.6% of the rectenna area (see Figure 30.). This is a maximum estimate of the loss.

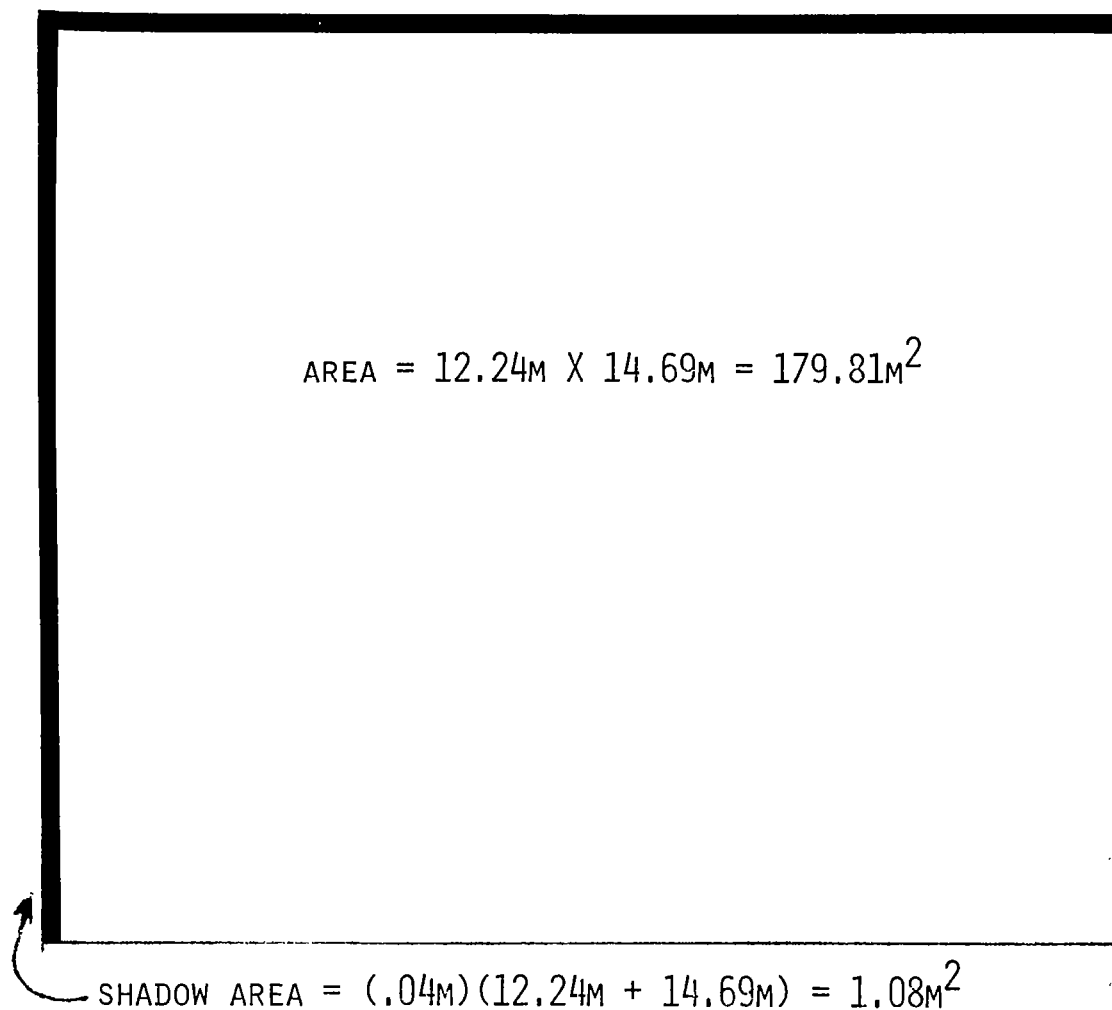


FIGURE 30

VI. MICROWAVE DIODE FAILURES DUE TO INDUCED CURRENT TRANSIENTS

The 25 W S GaAs diodes used in the design of the SPS rectenna have not been produced and no failure data is available for these devices. In order to obtain estimates of failure power of the diodes in the design, we used the specification data for the HP5082-2824 microwave diode and scaled the characteristics to 25 W using the "Wunsch relationship" described in the references below. We also obtained advice directly from Dr. D.C. Wunsch regarding the extrapolated power failure current.

1. Defense Department Report D224-13042-1 EMP, Susceptibility of Semiconductor Components, dated September, 1974.
2. Defense Department Report D224-10022-1 EMP, Electronic Analysis Handbook, dated May, 1973.
3. Defense Department Report D224-10019-1 EMP, Electronic Design Handbook, dated April, 1973.

Figure 31 shows the predicted failure power for 25 watt diodes, as a function of pulse width.

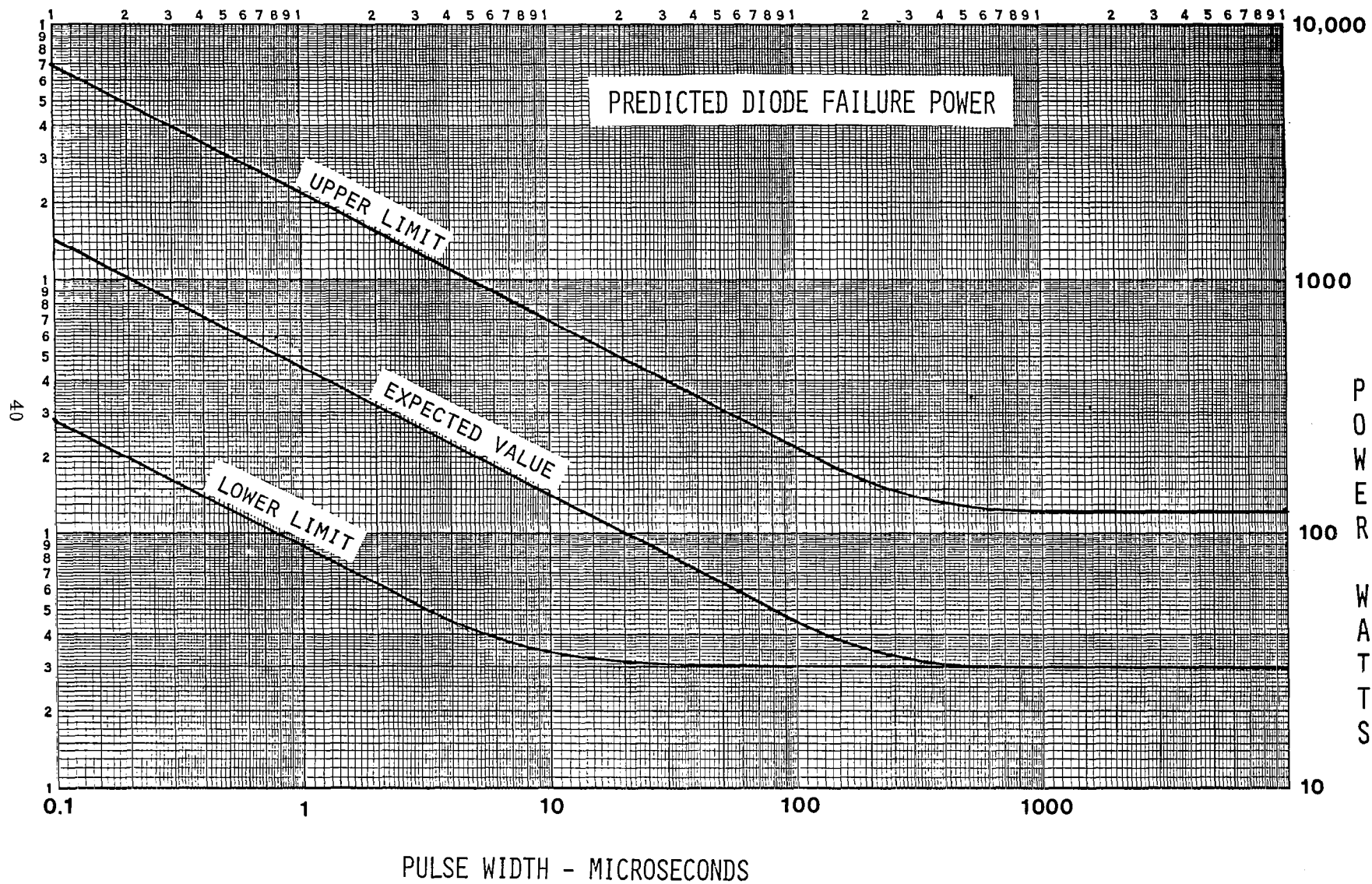


FIGURE 31

VII. COMPUTER SIMULATION OF ELECTROSTATIC FIELD AROUND AN SPS RECTENNA

The electrostatic fields produced by the charges on the lightning channel induce charges on the rectenna and on the lightning protection conductors. Changes in this electrostatic field require a redistribution of charge on the rectenna system; the resulting currents can cause diode failure even with a lightning grounding system in place. One output of the computer simulation of the electrostatic field around the SPS rectenna is an evaluation of the induced current on the rectenna with and without the recommended lightning protection equipment.

An additional output from the computer simulation is the potential around the rectenna billboard enabling us to estimate the enhancement factors of the electric field due to the billboard shape.

The algorithm used in the simulation computes an array of values for the potential around the middle of five infinitely long billboards. We assume here that the contribution to the local potential from billboards further away is ignorably small. The surface charge distribution on the billboards is simulated with ten infinitely long line charges evenly spaced along the billboard. The value for the line charges is determined interactively with the computer to produce a zero potential contour that has the same shape as the billboard. Figure 32 illustrates this simulation.

In order to compute the potential, we will need $U(x,y)$, the electrostatic potential at a point (x,y) in free space, where the coordinate system is such that the line of electrical charges giving rise to the potential is located at the origin. If we call the y -coordinate the height h , then $U(x,H)$ is the electrostatic potential at x and h of a line charge λ (coulomb/meter) at a height d directly above the point $x = 0$. There is also a contribution to U from the image charge. Thus,

$$U(x,h) = - \frac{\lambda}{2\pi\epsilon_0} \ln \left[\frac{x^2 + (h-d)^2}{x^2 + (h+d)^2} \right]^{1/2}.$$

From this, the potential distribution around the rectenna may be calculated. Let $U(l,h)$ be the potential at $x = l$ and $y = h$ due to a periodic system of line charges simulating the rectenna (see Figure 31.) We then have that

$$U(l,h) = \sum_{i=1}^N \sum_{j=1}^M \left(- \frac{\lambda_j}{2\pi\epsilon_0} \right) \ln \left[\frac{(l - L[i-1] - x_j)^2 + (h - s x_d)^2}{(l - L[i-1] - x_j)^2 + (h + s x_j)^2} \right]^{1/2},$$

where the free-space value for the dielectric constant is assumed and where

- i = Billboard number,
- j = Line charge number on billboard i ,
- s = Slope of billboard ($= \tan \alpha$),
- M = Number of line charges ($= 10$),
- N = Number of billboards ($= 5$).

SIMULATION OF SPS RECTENNA WITH LINE CHARGES

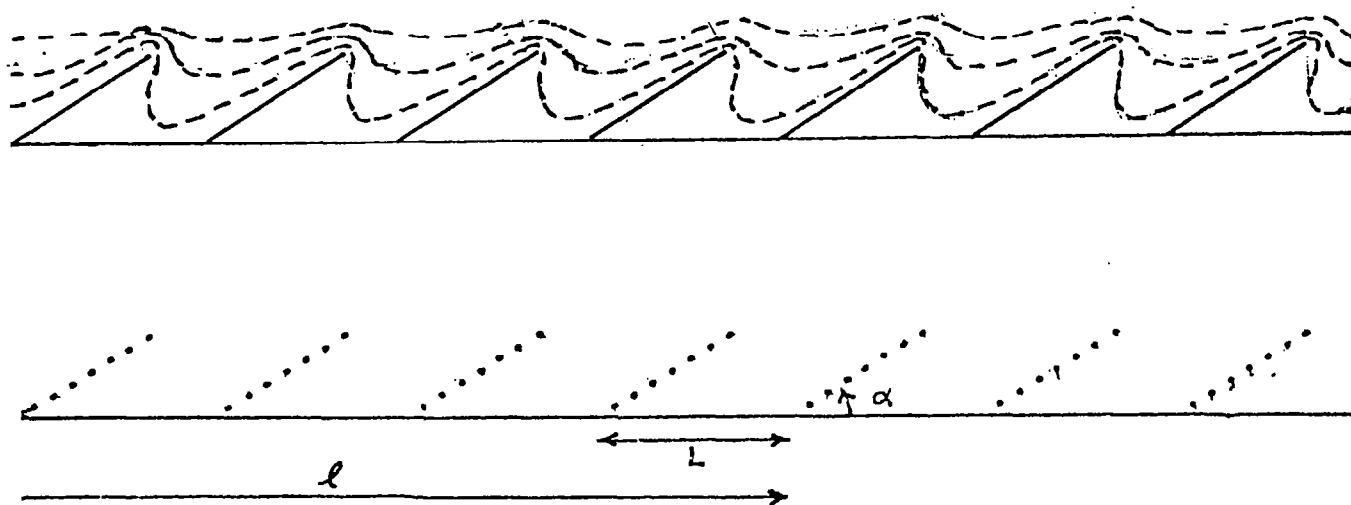


FIGURE 32

In the presence of a uniform electric field of 100,000 volts/meter (directed upward), ten line charges have been selected to produce the array of values shown in Figure 33. Three potential contours have been sketched (zero, 10,000 V, and 100,000 V) around the ten line charges on the billboard. The zero contour follows closely the position of the billboard surface, as required by the simulation algorithm. Note how closely spaced the contours are at the top edge of the billboard. Electric field enhancement factors of at least 6.5 exist in this region based upon our simulations. Higher resolution simulations would be required to refine the enhancement factor estimates.

The values obtained for the 10 individual line charges found for the solution shown in Figure 33 are (in $\mu\text{Coul./m}$):

0.36, 0.465, 0.572, 0.679, 0.924, 1.02, 1.14, 1.78, 2.91, 4.14.

We can convert these to a surface charge density by dividing each value by the billboard distance represented by the line charge. The first line charge serves approximately $3/2 \left(\frac{12.24}{10} \text{ m}\right)$; the last line charge serves $1/2 \left(\frac{12.24}{10} \text{ m}\right)$; and all others are associated with a length $\left(\frac{12.24}{10} \text{ m}\right)$.

Figure 34 is a plot of charge/unit area ($\mu\text{Coul./m}^2$) on the billboard as a function of length (northward) along the billboard surface.

When an additional line charge is placed at the position of the lightning static, and all of line charge values are adjusted to the new configuration, we find the simulated potential function around a protected billboard - Figure 35. The placement of the static in this example is based upon the discussion in Section I.2.3., with $L = 0.98\text{m}$, corresponding to $\alpha = 40^\circ$. The charge/unit length for the static is $4.6 \mu\text{Coul./m}$. The charge/unit lengths for the ten billboard line charges in ($\mu\text{Coul./m}$) are:

0.315, 0.47, 0.51, 0.57, 0.87, 0.89, 0.90, 1.35, 1.78, 2.1.

These line charges may be compared with the unprotected billboard charges corresponding to the solutions of Figure 35. The protected billboard charges approach approximately one-half of the corresponding unprotected charges.

The line charges used to simulate the rectenna are normalized to a charge/unit area through division by the associated lengths, as previously described, to obtain the induced charge distribution on the protected rectenna billboard.

Figure 36 is a plot of charge/unit area in $\mu\text{Coul./m}^2$ as a function of the distance (northward) along the billboard face.

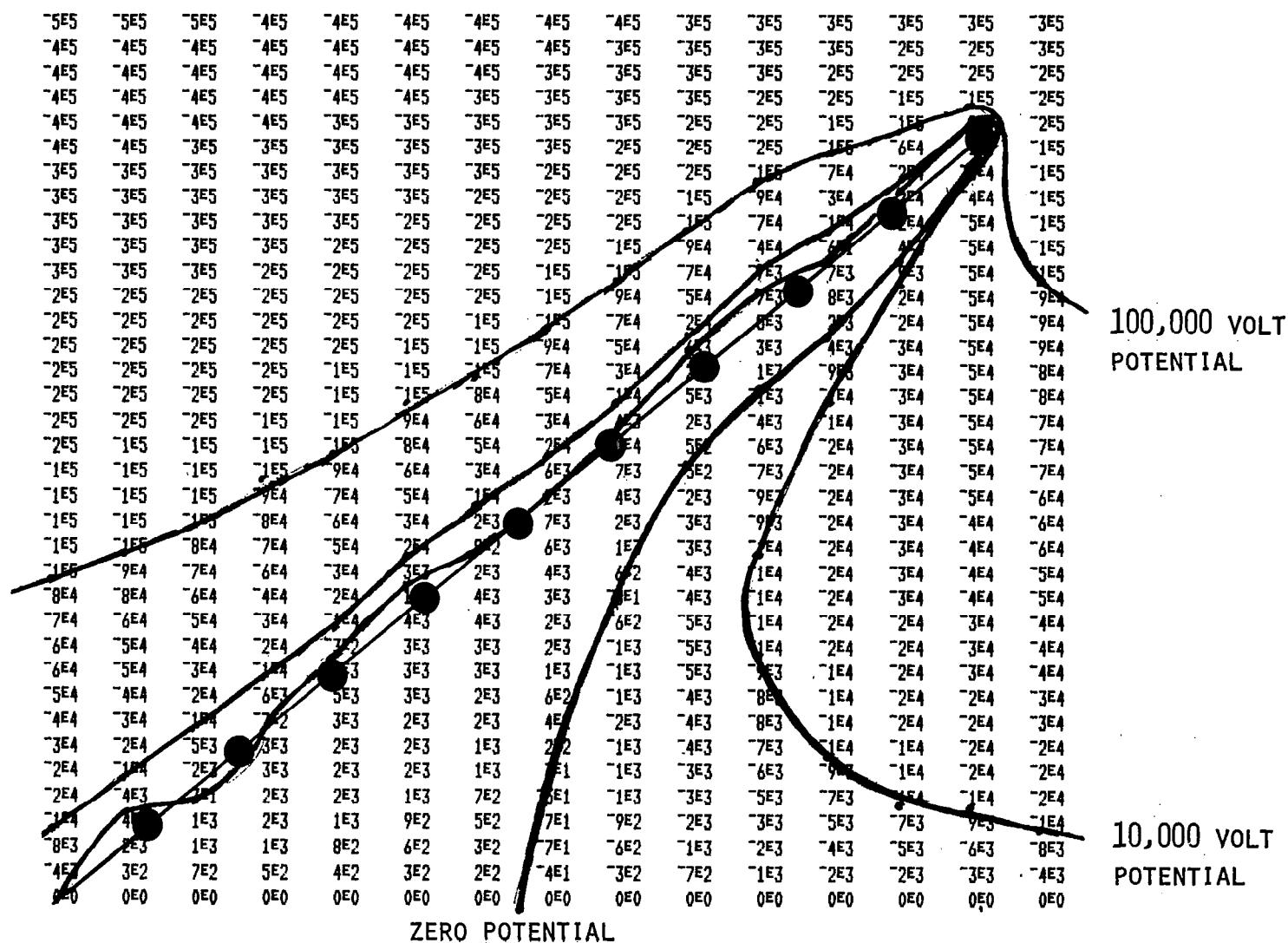


FIGURE 33

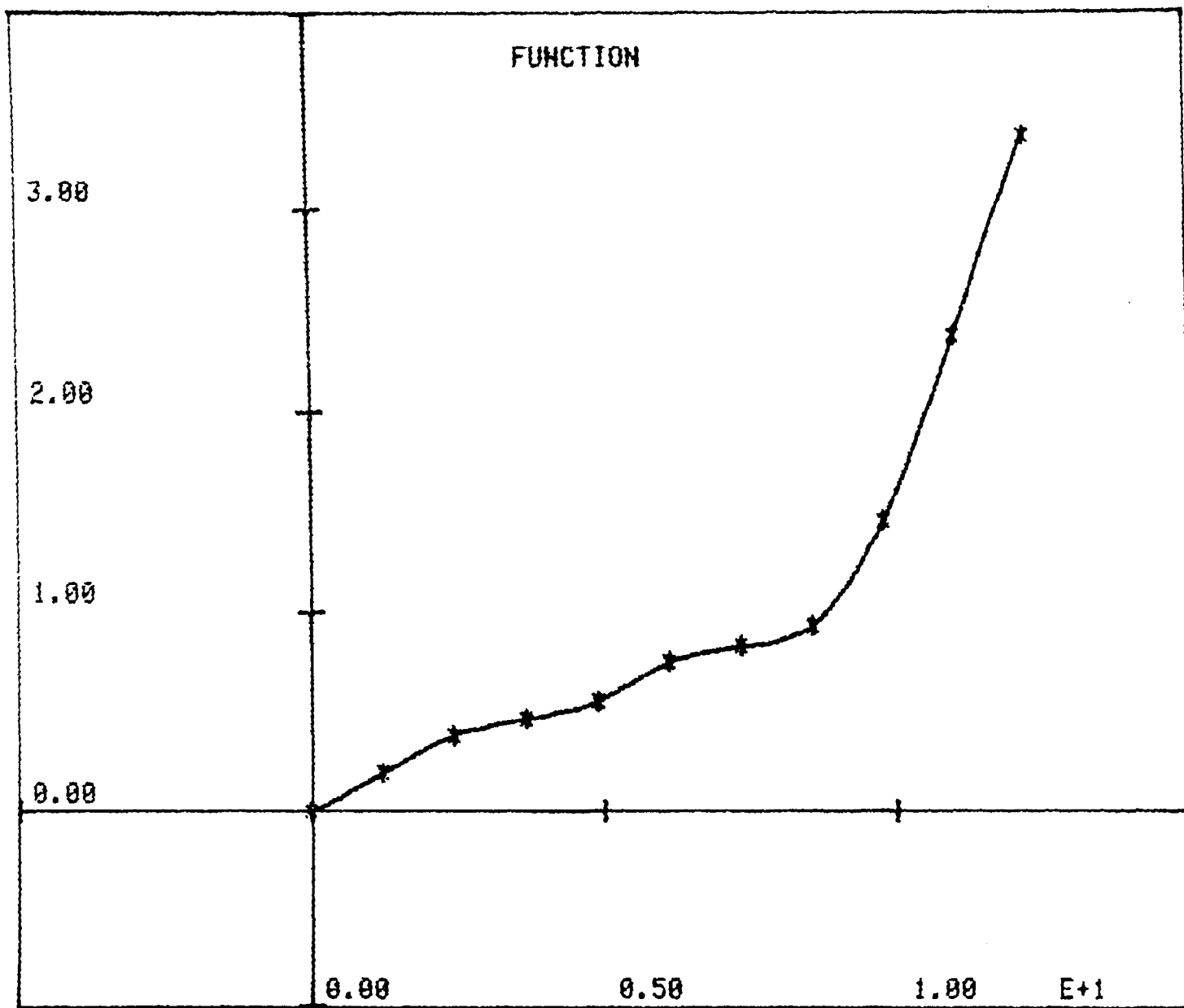
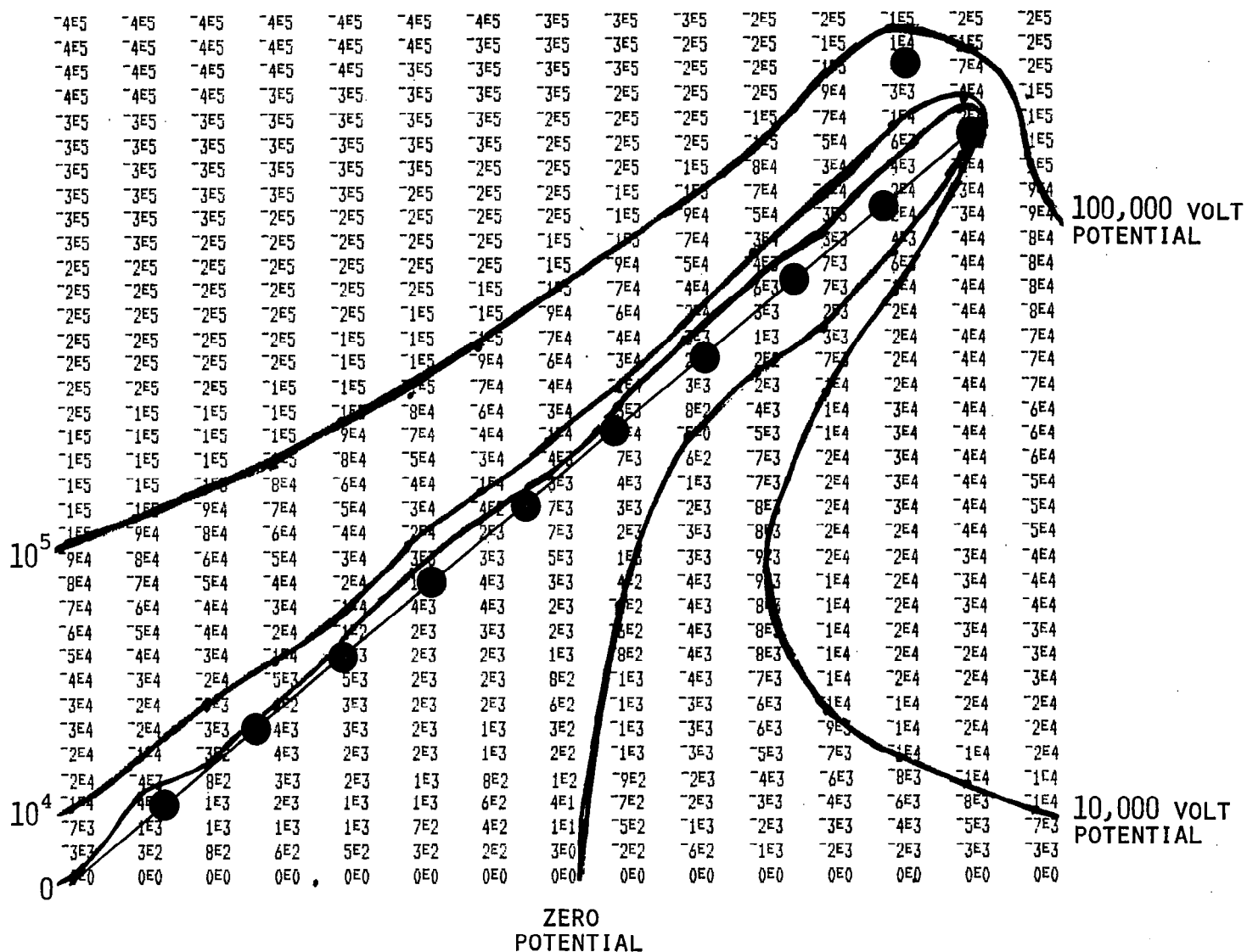


FIGURE 34



● LOCATION OF LINE CHARGES SIMULATING BILLBOARD

FIGURE 35

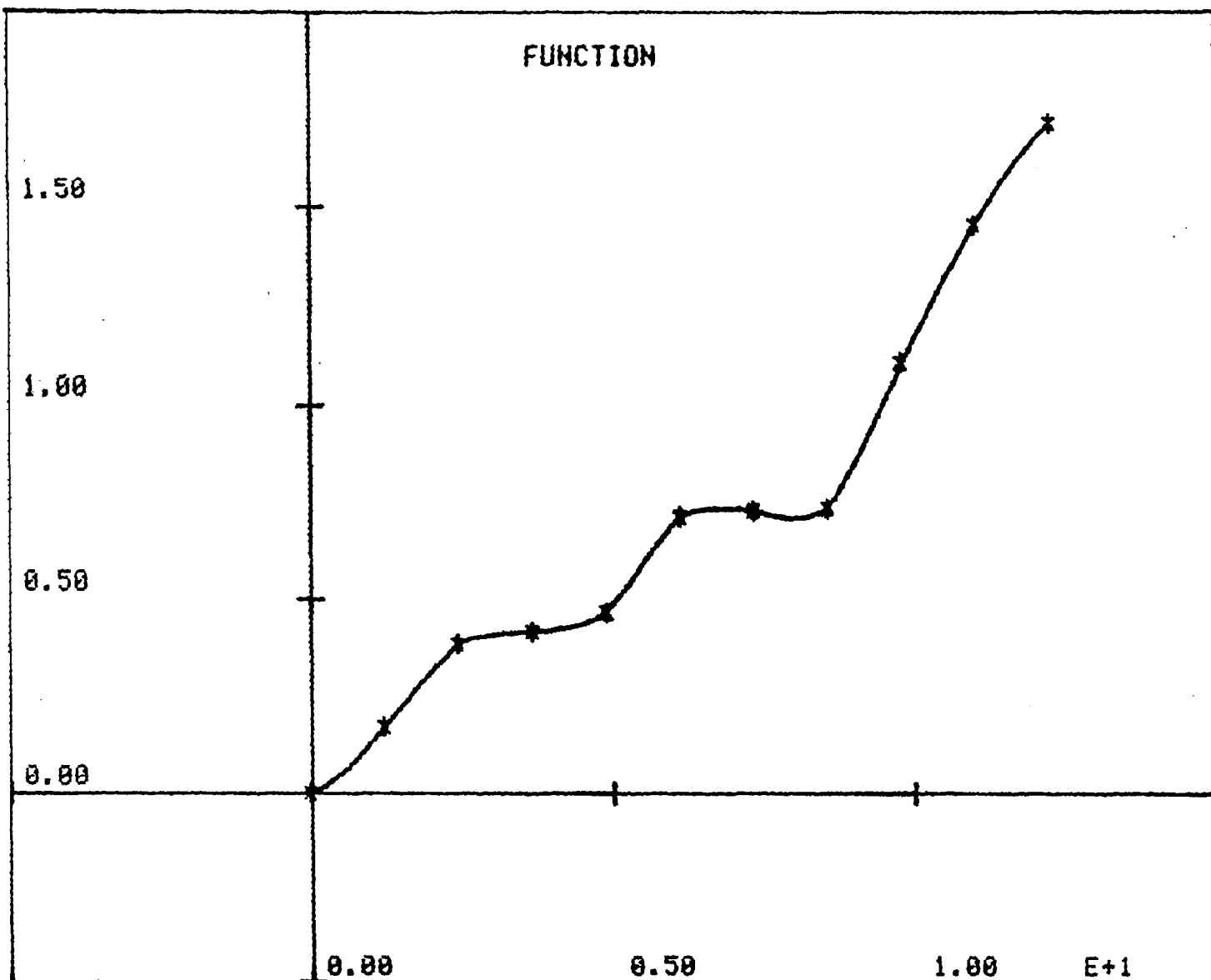


FIGURE 36

VIII. COMPUTATION OF LIGHTNING ELECTRIC FIELDS

In section VII, a rectenna was simulated in the presence of a uniform electric field of 100,000 Volts. The induced surface charges derived from the simulation are directly proportioned to the imposed electric field strength.

In this section we describe a computer program that was written to derive values for the lightning-produced electric fields as a function of time and of distance from "ground zero" - the point of strike. We have run the program for a range of lightning parameters obtained from actual measurements reported in the literature.

The program computes the contribution to the electric field from the thundercloud charge center participating in the cloud-to-ground flash, the charge on the lightning channel, and the images of these charges. All charges are allowed to vary with time in a manner consistent with observations [Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1977 Revision; Edited by John W. Kaufman, NASA Technical Memorandum 78118].

Figure 37 displays the relevant equations and configurations covering the leader phases of the computation.

In Figure 38 the equations and conditions during the return stroke portion are shown. The program used in computing the fields is provided in the appendix.

The material following Figure 38 provides the tabular and graphic data used in these computations for the return stroke phase. These data are contained in Figures (39-44) inclusive.

The output of the computer program is a "blow-by-blow" history of the electrical field at a specified distance from ground zero as a function of time. Figure 45 displays one section of the output from one of the computer runs. This corresponds to a worst-case situation, 10 meters away from the very-severe-model. The units of time are seconds (along the abscissa), and the units of the ordinate are kilovolts per meter.

Table 8.4 in figure 46 provides a summary of the output for the various computer runs. Listed are the peak negative fields, the peak positive fields (when positive fields occur), and the ΔE and ΔT for the portion of the flash with the peak rate of change of electric field.

These values are our input data to the computation of diode failure when used in conjunction with the induced surface charge results of the rectenna electrostatic simulations.

INITIAL SPECIFICATIONS

TEMPORAL FUNCTIONS:

$$X = Y_0 - V_{LT}$$

$$Q = Q_0 - P_L (Y - X)$$

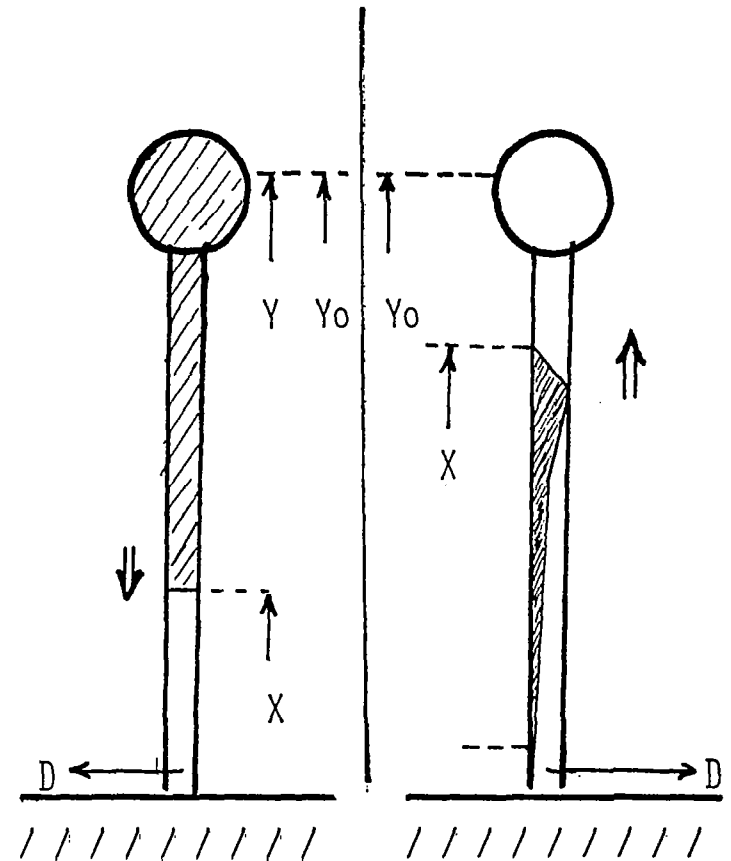
$$\left\{ \begin{array}{l} Y_0 \text{ } (\sim 5 \text{ KM}) \\ Q_0 \text{ } (\sim -10 \text{ Coul}) \\ V_L \text{ } (\sim 10^5 \text{ m/s}) \\ \tau = 0, \quad Y = Y_0 \\ Q_L \text{ } (\sim -5 \text{ Coul}) \\ P = P_L = Q_L / Y_0 \end{array} \right.$$

SOLVE FOR $E_L(\tau, D)$ FOR $\tau \leq \tau_L$ WHERE

$$\tau_L = (Y_0 - X_L) / V_L$$

X_L (~ 50 METERS)

FOR $T > T_L$, $E_L(T, D) = E_L(T_L, D)$



$$E = \frac{2P}{4\pi\epsilon_0} \left\{ \frac{1}{(D^2 + X^2)^{1/2}} - \frac{1}{(D^2 + Y^2)^{1/2}} \right\} + \frac{2QY_0}{4\pi\epsilon_0 (D^2 + Y_0^2)^{3/2}}$$

FIGURE 37

RETURN STROKE PROCESS:

INITIAL SPECIFICATIONS

TEMPORAL FUNCTIONS:

$$Y = V_R T'$$

$$Y_0, Q_0, Q_L$$

SAME AS LEADER PROCESS

$$T' = T - T_L$$

$$V_R (\sim 5 \times 10^7 \text{ m/s})$$

$$x = 0 \quad \left\{ \begin{array}{l} \text{SIGN} \\ \text{OPPOSITE} \\ \text{TO } Q_0 \end{array} \right.$$

$$I(T)$$

$$\left. \begin{array}{l} P = \int I dT / Y \\ Q = 0 \end{array} \right\} \text{ FOR } Y < Y_0$$

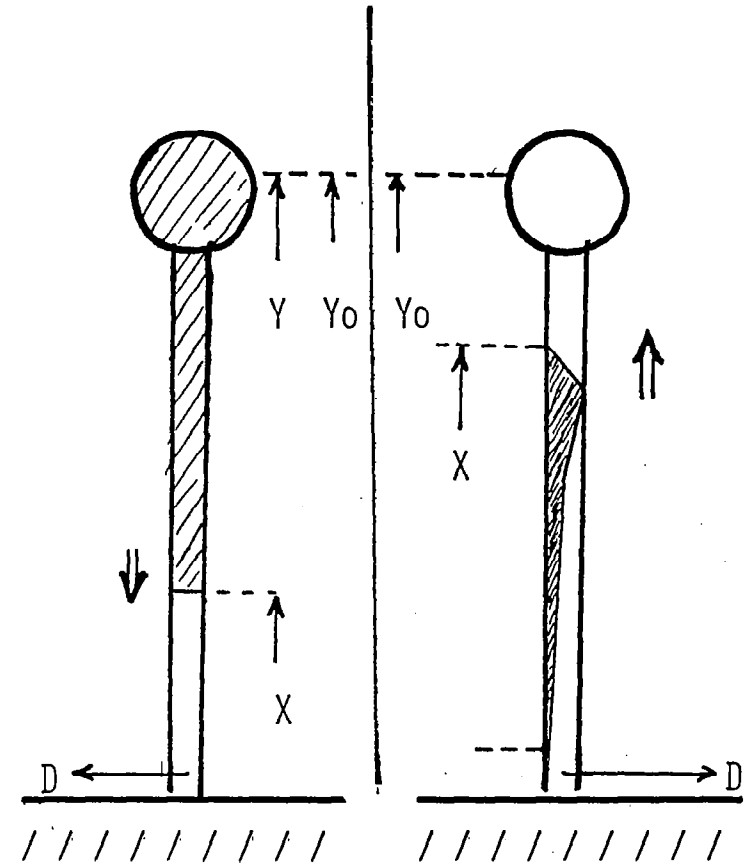
$$\left. \begin{array}{l} P = \int I dT / Y_0 \\ Q = 0 \end{array} \right\} \text{ FOR } Y > Y_0 \quad \text{AND} \quad P \leq -P_L$$

$$\left. \begin{array}{l} P = -P_L \\ Q = \int I dT + Q_L \end{array} \right\} \text{ FOR } Y > Y_0 \quad \text{AND} \quad P > -P_L$$

SOLVE FOR $E_R(T', D)$ FOR $T > T_L$ OR $T' > 0$

$$\text{TOTAL FIELD } E_T(T, D) = E_L(T_L, D) + E_R(T, D)$$

TERMINATE COMPUTATION WHEN $Q \geq -(Q_0 - Q_L)$



$$E = \frac{2P}{4\pi\epsilon_0} \left\{ \frac{1}{(D^2 + X^2)^{1/2}} - \frac{1}{(D^2 + Y^2)^{1/2}} \right\} + \frac{2 \cdot QY_0}{4\pi\epsilon_0 (D^2 + Y_0^2)^{3/2}}$$

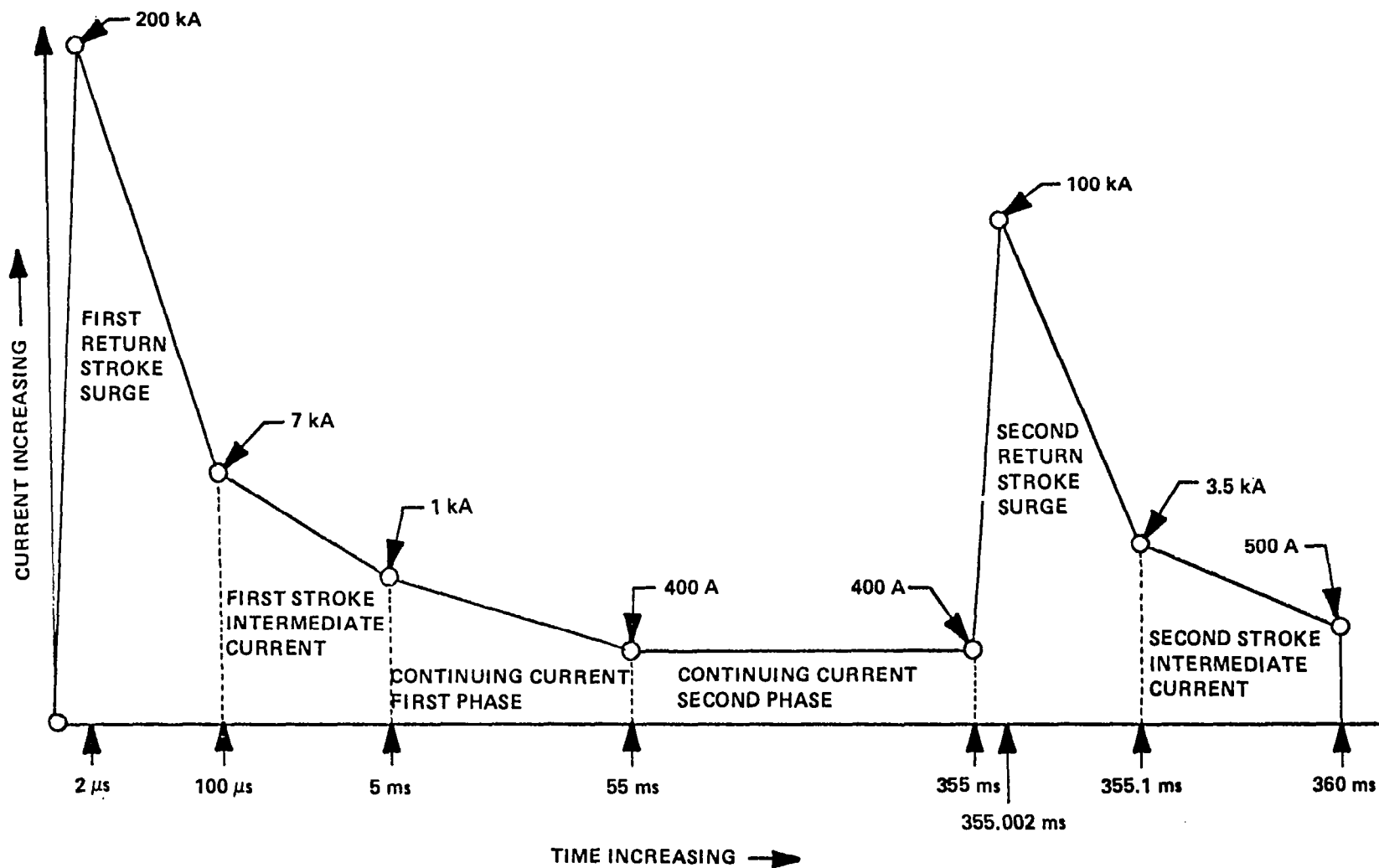
FIGURE 38

DETAILS OF A VERY SEVERE LIGHTNING MODEL (MODEL 1)

Stage	Key Points	Rate of Current Change	Charge Passing
1. First Return Stroke Surge	$t = 0$ $i = 0$ $t = 2 \mu s$ $i = 200 \text{ kA}$ $t = 100 \mu s$ $i = 7 \text{ kA}$	Linear Rise - $100 \text{ kA}/\mu s$ Linear Fall - 193 kA in $98 \mu s$	0.2 C^* $\sim 10.2 \text{ C}$
2. First Stroke Intermediate Current	$t = 100 \mu s$ $i = 7 \text{ kA}$ $t = 5 \text{ ms}$ $i = 1 \text{ kA}$	Linear Fall - 6 kA in 4.9 ms	19.6 C
3. Continuing Current--First Phase	$t = 5 \text{ ms}$ $i = 1 \text{ kA}$ $t = 55 \text{ ms}$ $i = 400 \text{ A}$	Linear Fall - 600 A in 50 ms	35.0 C
4. Continuing Current--Second Phase	$t = 55 \text{ ms}$ $i = 400 \text{ A}$ $t = 355 \text{ ms}$ $i = 400 \text{ A}$	Steady Current	120.0 C
5. Second Return Stroke Surge	$t = 355 \text{ ms}$ $i = 400 \text{ A}$ $t = 355.002 \text{ ms}$ $i = 100 \text{ kA}$ $t = 355.1 \text{ ms}$ $i = 3.5 \text{ kA}$	Linear Rise $\sim 50 \text{ kA}/\mu s$ Linear Fall - 96.5 kA in $98 \mu s$	$\sim 0.1 \text{ C}$ $\sim 5.1 \text{ C}$
6. Second Stroke Intermediate Current	$t = 355.1 \text{ ms}$ $i = 3.5 \text{ kA}$ $t = 360 \text{ ms}$ $i = 500 \text{ A}$	Linear Fall - 3 kA in 4.9 ms	9.8 C

* Coulomb (C) is the quantity of electricity transported in one second by a current of one ampere.

FIGURE 39



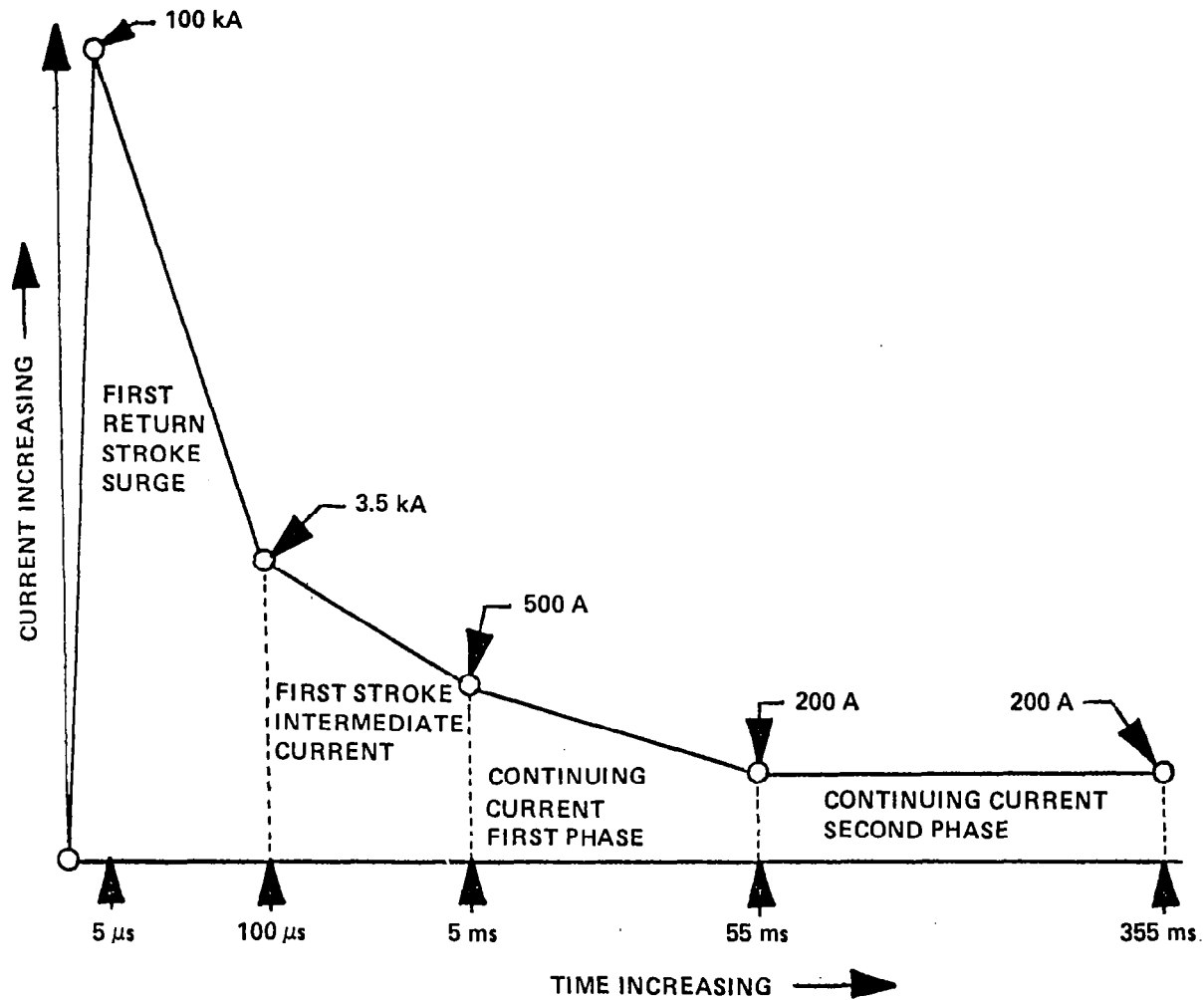
DIAGRAMMATIC REPRESENTATION OF A VERY SEVERE LIGHTNING MODEL
(MODEL 1) (Note that the diagram is not to scale)

FIGURE 40

DETAILS OF A 98 PERCENTILE PEAK CURRENT LIGHTNING MODEL (MODEL 2)

Stage	Key Points	Rate of Current Change	Charge Passing
1. First Return Stroke Surge	$t = 0$ $i = 0$ $t = 5 \mu s$ $i = 100 \text{ kA}$ $t = 100 \mu s$ $i = 3.5 \text{ kA}$	$\left\{ \begin{array}{l} \text{Linear Rise} - 20 \text{ kA}/\mu s \\ \text{Linear Fall} - 96.5 \text{ kA in } 95 \mu s \end{array} \right.$	0.3 C $\sim 4.9 \text{ C}$
2. First Stroke Intermediate Current	$t = 100 \mu s$ $i = 3.5 \text{ kA}$ $t = 5 \text{ ms}$ $i = 500 \text{ A}$	$\left\{ \begin{array}{l} \text{Linear Fall} - 3 \text{ kA in } 4.9 \text{ ms} \end{array} \right.$	9.8 C
3. Continuing Current--First Phase	$t = 5 \text{ ms}$ $i = 500 \text{ A}$ $t = 55 \text{ ms}$ $i = 200 \text{ A}$	$\left\{ \begin{array}{l} \text{Linear Fall} - 300 \text{ A in } 50 \text{ ms} \end{array} \right.$	17.5 C
4. Continuing Current--Second Phase	$t = 55 \text{ ms}$ $i = 200 \text{ A}$ $t = 355 \text{ ms}$ $i = 200 \text{ A}$	Steady Current	60 C

FIGURE 41



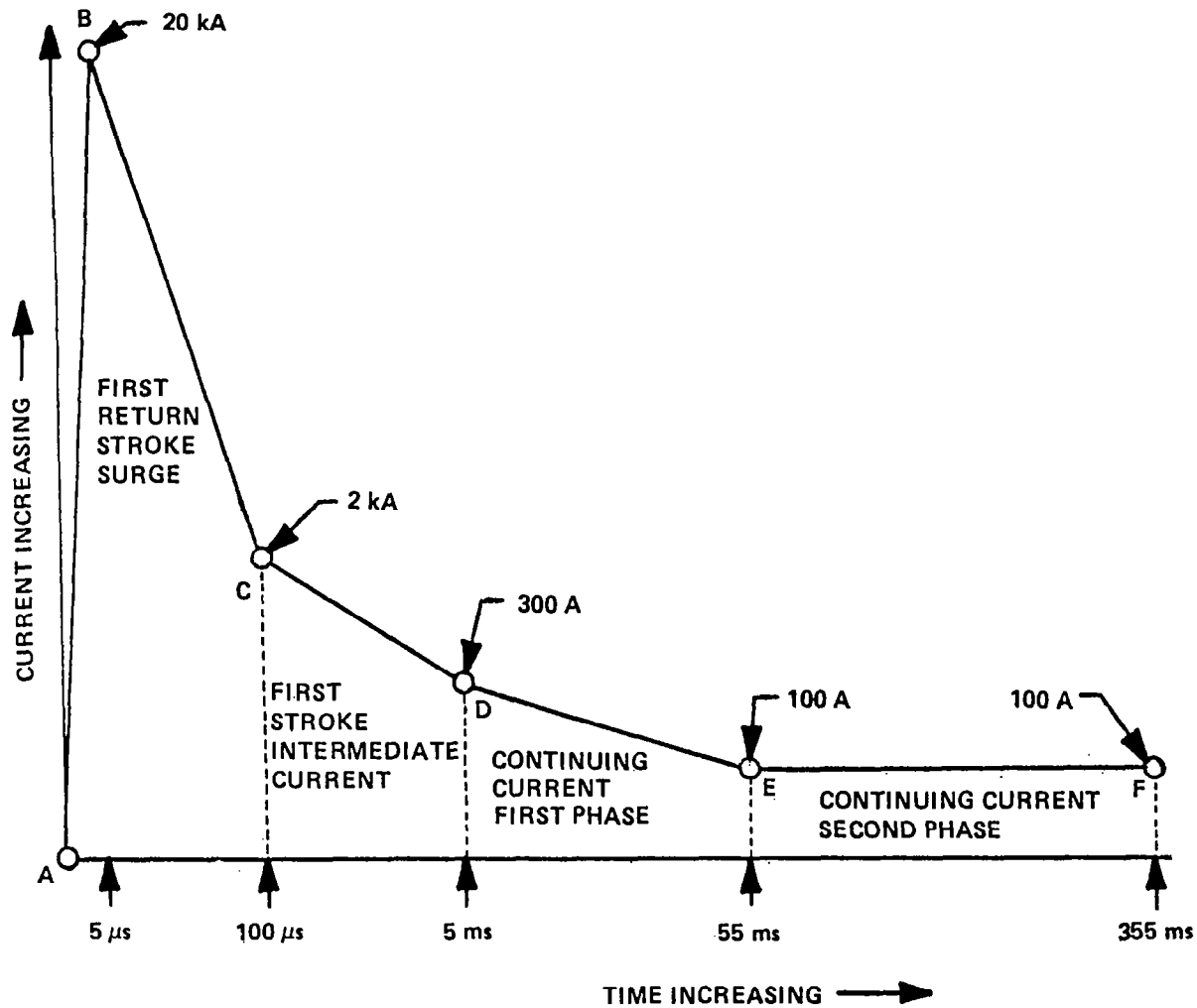
DIAGRAMMATIC REPRESENTATION OF A 98 PERCENTILE PEAK CURRENT LIGHTNING MODEL (MODEL 2) (Note that the diagram is not to scale.)

FIGURE 42

DETAILS OF AN AVERAGE LIGHTNING MODEL (MODEL 3)

Stage	Key Points	Rate of Current Change	Charge Passing
1. First Return Stroke Surge	$t = 0$ $i = 0$ $t = 5 \mu s$ $i = 20 \text{ kA}$ $t = 100 \mu s$ $i = 2 \text{ kA}$	} Linear Rise - $4 \text{ kA}/\mu s$ } Linear Fall - 18 kA in $95 \mu s$	0.1 C $\sim 1.0 \text{ C}$
2. First Stroke Intermediate Current	$t = 100 \mu s$ $i = 2 \text{ kA}$ $t = 5 \text{ ms}$ $i = 300 \text{ A}$	} Linear Fall - 1.7 kA in 4.9 ms	5.6 C
3. Continuing Current -- First Phase	$t = 5 \text{ ms}$ $i = 300 \text{ A}$ $t = 55 \text{ ms}$ $i = 100 \text{ A}$	} Linear Fall - 200 A in 50 ms	10.0 C
4. Continuing Current -- Second Phase	$t = 55 \text{ ms}$ $i = 100 \text{ A}$ $t = 355 \text{ ms}$ $i = 100 \text{ A}$	Steady Current	30.0 C

FIGURE 43



DIAGRAMMATIC REPRESENTATION OF AN AVERAGE LIGHTNING MODEL
(MODEL 3) (Note that the diagram is not to scale.)

FIGURE 44

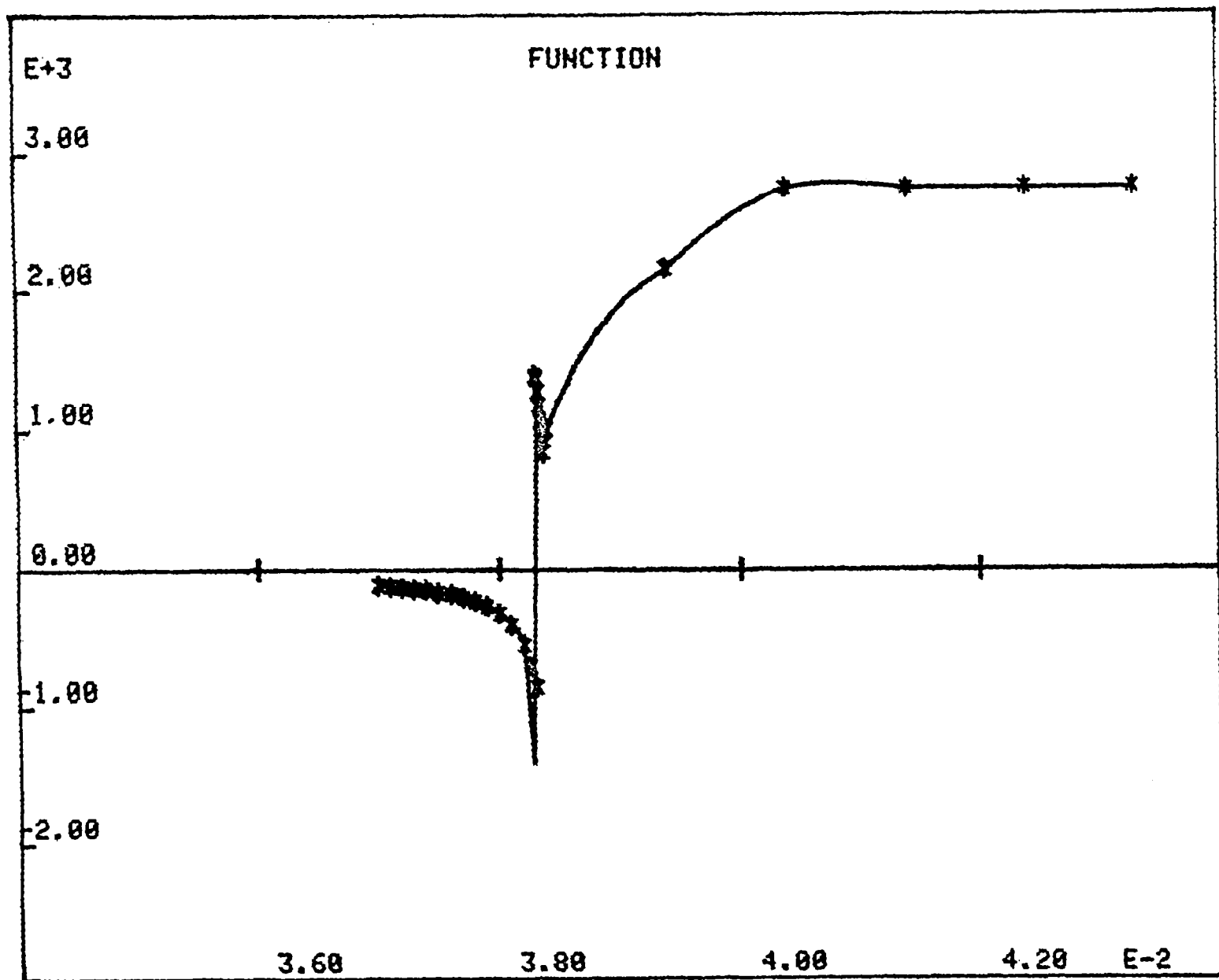


FIGURE 45

TABLE 8.4

Distance	VERY SEVERE MODEL			98 PERCENTILE MODEL			AVERAGE MODEL		
	Peak Negative	Peak Positive	$\frac{\Delta E/\Delta T}{\text{Peak}}$	Peak Negative	Peak Positive	$\frac{\Delta E/\Delta T}{\text{Peak}}$	Peak Negative	Peak Positive	$\frac{\Delta E/\Delta T}{\text{Peak}}$
10 m	-8.5×10^5	2.8×10^6	$\frac{2.2 \times 10^6}{1.2 \times 10^{-5}}$	-5.95×10^5	1.81×10^6	$\frac{6.46 \times 10^5}{3.00 \times 10^{-6}}$	-5.09×10^5	1.30×10^6	$\frac{5.68 \times 10^5}{2.59 \times 10^{-5}}$
50 m	-5.7×10^5	1.7×10^5	$\frac{4.37 \times 10^5}{2.2 \times 10^{-5}}$	-3.88×10^5	1.04×10^5	$\frac{3.59 \times 10^5}{2.5 \times 10^{-5}}$	-3.10×10^5	6.1×10^4	$\frac{1.14 \times 10^5}{2.50 \times 10^{-5}}$
100 m	-3.49×10^5	2.49×10^4	$\frac{2.15 \times 10^5}{2.2 \times 10^{-5}}$	-2.36×10^5	N/A	$\frac{1.75 \times 10^5}{2.5 \times 10^{-5}}$	-1.85×10^5	N/A	$\frac{5.47 \times 10^4}{3.5 \times 10^{-5}}$
500 m	-8.94×10^4	N/A	$\frac{3.79 \times 10^4}{3.2 \times 10^{-5}}$	-6.15×10^4	N/A	$\frac{2.96 \times 10^4}{4.5 \times 10^{-5}}$	-5.12×10^4	N/A	N/A
1000 M	-5.35×10^4	N/A	$\frac{1.69 \times 10^4}{4.2 \times 10^{-5}}$	-2.61×10^4	N/A	N/A	-3.29×10^4	N/A	N/A

FIGURE 46

IX. COMPUTATIONS OF DIODE FAILURE

We are now to the point of having generated all of the data that are required to evaluate the conditions under which the microwave rectifier diodes will fail due to induced currents from nearby lightning flashes. For a given ΔE and ΔT (from Table 8.4) we obtain from Figure 31 the power required for diode failure and from Figure 32 the induced charge/unit area on the rectenna surface. We assume that a diode designed to operate at 67 V will have a breakdown voltage of about 100 Volts.

The surface area of the rectenna that has an induced surface charge of the size sufficient to cause diode failure is then computed from comparison with areas of the rectenna served by individual diodes and by series strings of diodes. Sample computations follow.

SAMPLE COMPUTATION OF DIODE FAILURE (98TH PERCENTILE - 10 METER - NO PROTECTION)

1. 98 percentile model - 10 meters: $\Delta T = 3 \times 10^{-6}$ and $\Delta E = 6.46 \times 10^5$.
2. Expected diode failure power from Figure 30: 250 Watts.
3. Energy dissipated in the diode: $250 \text{ Watts} \times 3 \times 10^{-6} \text{ s} = 7.5 \times 10^{-4}$ Joules.
4. Charge transferred across 100 Volts diode breakdown voltage = 7.5×10^{-6} Coulombs.
5. From ΔE in step 1 and figure 37, the induced charge/unit area = $3 \times 10^{-6} \text{ C/m}^2 \times 6.46 = 19.38 \times 10^{-6} \text{ C/m}^2$.
6. From steps 4 and 5, the rectenna area with surface charge equivalent to the charge required to cause diode failure is: 0.39 m^2 .
7. Area served by diodes: rectenna center, .
$$\frac{25 \text{ watts}}{230 \text{ w/m}^2} = 0.11 \text{ m}^2; \text{ rectenna edge, } \frac{25 \text{ watts}}{10 \text{ w/m}^2} = 2.5 \text{ m}^2.$$
8. Compare 6 with 7: single diode configuration near rectenna center is safe. Single diode configuration near rectenna edge is vulnerable.
9. However, the diodes are to be put in series (597 to a string) hence the diodes near the bottom must carry all of the induced current to the entire string. For these bottom-string diodes the area served with respect to the induced charge is: rectenna center, 60 m^2 ; rectenna edge, 1400 m^2 .
10. To protect against the 98 percentile flash within 10 meters of ground zero would require fast surge protection diodes (back to back zeners) on all diodes in the rectenna. This extent of protection may not be cost effective; however the considerations in Section X indicate that simpler protection arrangements will probably be effective near the rectenna center.

FAILURES PRODUCED BY THE AVERAGE LIGHTNING FLASH

The situation considered here is the extent of the protection required for an "average" lightning flash if we are willing to accept losses from the extreme cases.

The computation sequence follows the same procedure described immediately above. Here we use data for the average flash from Table 8.4 at a 10 m distance from ground zero.

SAMPLE COMPUTATION OF DIODE FAILURE
(AVERAGE FLASH, 10 M, WITH "STATIC" PROTECTION)

1. From Table 8.4: $\Delta E = 5.68 \times 10^5$ v/m; $\Delta T = 2.59 \times 10^{-5}$ s.
2. From Figure 6.1: 80 watts.
3. $80 \text{ w} \times 2.59 \times 10^{-5} \text{ s} \approx 2 \times 10^{-3}$ Joules.
4. 2×10^{-5} coulombs.
5. From 1 and Figure 38: $1.5 \times 10^{-6} \times 5.68 = 8.52 \times 10^{-6}$ coul/m².
6. From 4 and 5: Area = 2.35 m².
7. Since the rectenna area served by individual diodes even on the edge $< 2.5 \text{ m}$, the individual diodes are self-protecting and able to take an "average" lightning flash.
8. However, when arranged in a series stack of 597, the diodes at the bottom of the stack must conduct the induced currents for the whole stack. The diodes cannot safely carry these currents.

X. LIGHTNING PROTECTION FOR SERIES DIODE STRINGS

As demonstrated in Section IX, the connection of microwave rectifier diodes in series requires special lightning protection considerations. We cannot make specific recommendations for these protection devices at this time because the rectenna current design is not advanced to the point that allows such detailed analysis. Rockwell International has provided us with an equivalent circuit for the rectenna; a slightly modified form of that circuit is shown in Figure 46. We have assumed that the series connections are to be made at the points indicated by the large spots and that the output filter operates around 30 Hz. A series string of rectenna elements of this design can be protected with a variety of methods. One cost-effective means is a spark gap arrangement incorporated in the diode feedthroughs, or the output filter inductors, or on the billboard configuration itself.

RECTENNA EQUIVALENT CIRCUIT AT 2.45 GHz

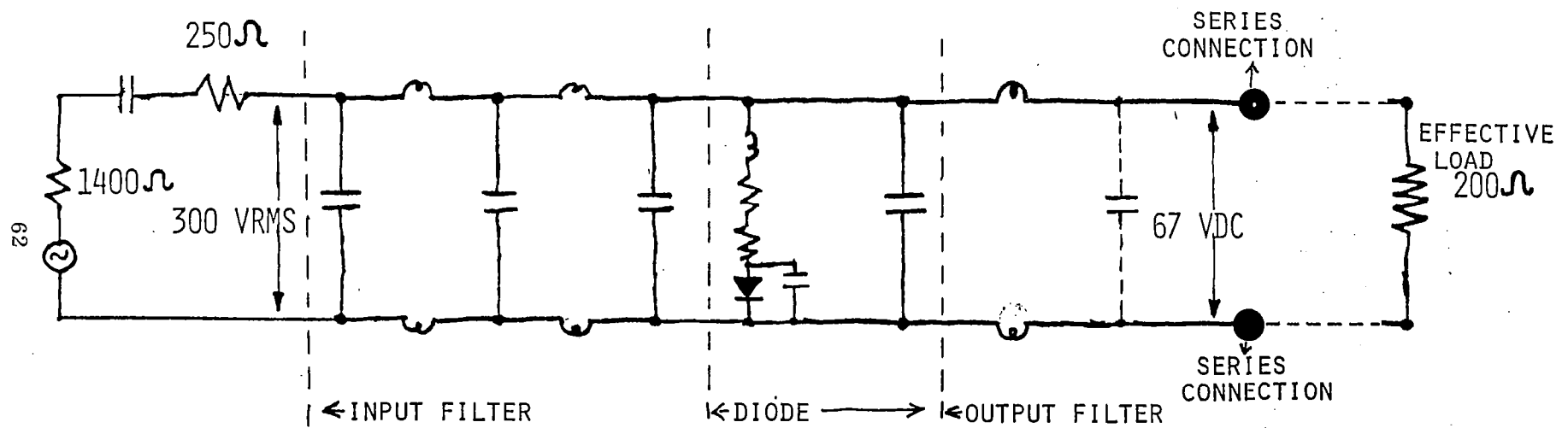


FIGURE 46

XI. CLOUD-TO-GROUND LIGHTNING DISTRIBUTION IN THE UNITED STATES

In order to have a working estimate of the hazard presented by lightning to rectennas, we need to know the cloud-to-ground lightning flash density for various possible rectenna sites in the United States. The cloud-to-ground lightning flash density (in $\#/km^2$ for example) is not a parameter that is measured as a climatological variable. We have found it necessary to use the number-of-thunderstorm days as a proxy variable because it is available as a climatological variable. Figure 47 gives contours of annual number-of-thunderstorm days.

XI.1. Pierce Conversion Formula

Several attempts have been made to derive a conversion formula to convert thunderstorm days into the flash density by using lightning flash counters in research areas for correlation with the count of thunderstorm days. The best of the various conversion formulas is that due to E.T. Pierce ("A Relationship Between Thunderstorm Days and Lightning Flash Density," Trans. AGU, 49, 686, 1967.) The Pierce formula (as does most others) has a quadratic term, which reflects the relationship between frequencies of local storms and storm intensity. In addition, the formula utilizes the monthly thunderstorm days as opposed to the annual average in order to incorporate seasonal effects in the conversion formula.

This formula is

$$q_M^2 = aT_M + a^2T_M^4,$$

where: T_M = monthly number of thunderstorm days and q_M is the monthly ground flash density ($\#/km^2/Mt.$) The parameter a is,

$$a = 3 \times 10^{-2}$$

If σ is the annual ground flash density ($\# km^{-2}/yr.$), then

$$\sigma = \sum_{M=1}^{12} q_M^2.$$

XI.2. Climatological Data -- Number of Thunderstorm Days

The inputs needed to compute the U.S. Distribution of ground lightning flash density are: (1) The monthly number of thunderstorm days for all U.S. stations recording these observations, (2) the coordinates of the observing sites, and (3) the computer software to compute the density and display the results geographically.

Items 1 and 2 were obtained from "Local Climatological Data - Annual Summaries for 1977" published by The National Oceanic and Atmospheric Administration on magnetic tape. The geographic plotting software of Item 3 was obtained from The National Technical Information Service, and the computer programming was done by J.L. Bohannon at Rice.

A detailed list of flash density for all of the stations used is provided in the Appendix.

Note the hot spots on the contours in Figure 48 that result when stations are located near geographic features that promote local thunderstorms. There are probably other similar hot spots in the U.S. that do not show up on this display because of the absence of an observing station nearby.

UNITED STATES DISTRIBUTION OF THE NUMBER OF THUNDERSTORM DAYS

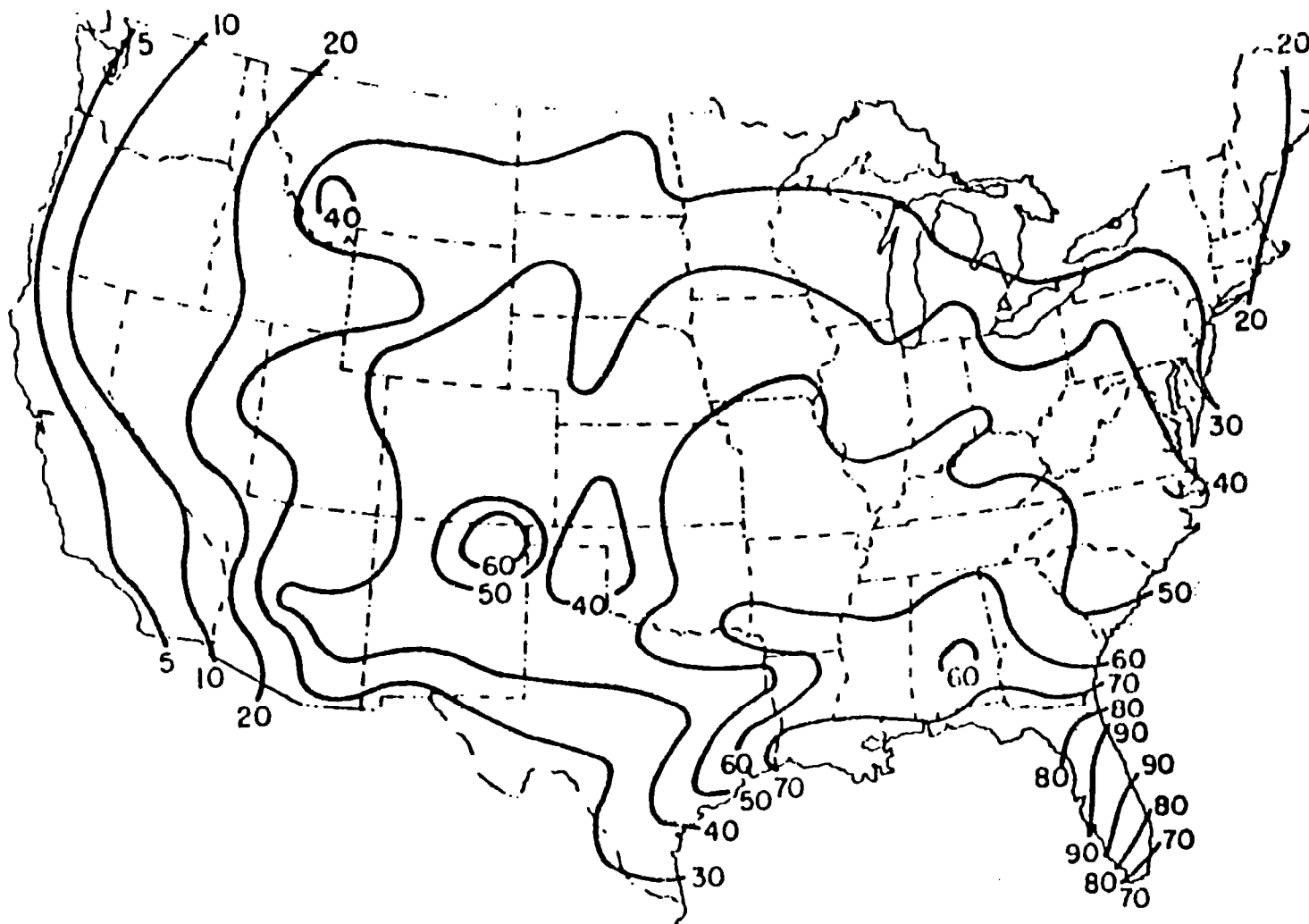


FIGURE 47

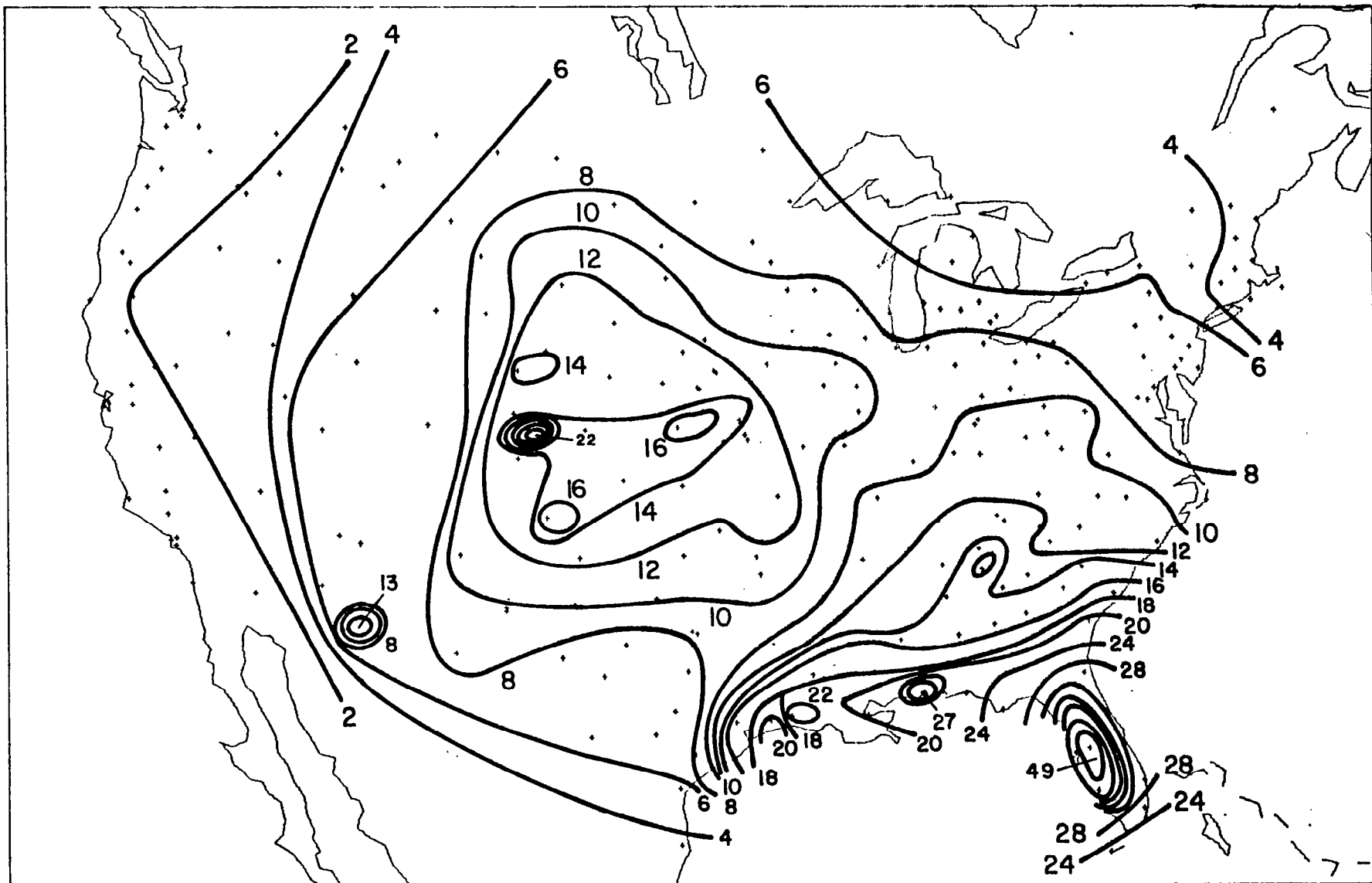


FIGURE 48

APPENDICES

Computer programs developed under this contract.

All programs are in FORTRAN H, unless otherwise specified. All of the programs were run on an IBM 370/155 and/or an Ite1 AS/6 computer.

Appendix A

Computer Program PANEL: A Computer Model of the SPS Plasma Interaction

The following pages are the listing of the program "PANEL," written to model the interaction of a high voltage solar array with an ambient Maxwellian plasma. The program was originally written by Dr. Lee W. Parker and was modified for application to the SPS problem by David L. Cooke.

Figure 1 shows a 10x10 grid of 100 cells. Each cell contains a number from 1 to 10. The numbers are arranged in a pattern that resembles a staircase or a series of connected paths. The numbers 1 through 10 are distributed across the grid, with some numbers appearing multiple times. The pattern is complex and non-linear, with numbers 1 and 10 appearing at the top and bottom edges, and numbers 2 through 9 filling the interior.

[illegible][illegible]

COMPILER OPTIONS = NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

C
C      SOLAR PANEL PROBLEM
ISN 0002      COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,
ISN 0003      1 TVOLTS,CUR,XMETER
COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005      COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
ISN 0006      COMMON/INTER/INT,IIA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,
1XI(30),YJ(20),ZK(10)
ISN 0007      DIMENSION DATE(20)
ISN 0008      DIMENSION VFC(4),IF(4),JF(4),KF(4)
ISN 0009      INTEGER SKPRFL,SKPLST,SKPCO
ISN 0010      NF(IX,JX,KX)=IX+II*(JX-1)+II*JJ*(KX-1)
ISN 0011      L=5
ISN 0012      M=6
ISN 0013      100 READ(L,9999,END=99) DATE
ISN 0014      9999 FORMAT(20A4)
ISN 0015      2 WRITE(M,9998) DATE
ISN 0016      9998 FORMAT(42H1SOLAR PANEL ELECTRIC FIELD AND CURRENTS. ,20A4)
C
C      READ GEOMETRIC PARAMETERS
ISN 0017      READ(L,111) IIP,IIM,JJP,JJM,KK,IV,JV
ISN 0018      II=IIM+IIP-1
ISN 0019      JJ=JJM+JJP-1
ISN 0020      NTOT=II*JJ*KK
ISN 0021      READ(L,222) (XP(I),I=1,IIP)
ISN 0022      READ(L,222) (XM(I),I=1,IIM)
ISN 0023      READ(L,222) (YP(J),J=1,JJP)
ISN 0024      READ(L,222) (YM(J),J=1,JJM)
ISN 0025      READ(L,222) (ZZ(K),K=1,KK)
C
C      READ PANEL POTENTIALS
ISN 0026      READ(L,116) (VP(I),I=1,IV),VRF
ISN 0027      READ(L,111) SKPRFL,SKPLST,ILX,IUX,KLK,KUK,MBD,NFPS,SKPCO
ISN 0028      DO 140 NPC=1,NTOT
ISN 0029      X(NPC,1)=0
ISN 0030      140 X(NPC,2)=0
ISN 0031      JIM1=IIM+IV-1
ISN 0032      JJM1=JJM+JV-1
ISN 0033      DO 150 I=IIM,IIM1
ISN 0034      DO 150 J=JJM,JJM1
ISN 0035      III=I+1-IIM
ISN 0036      N=NF(I,J,1)
ISN 0037      X(N,1)=VP(III)
ISN 0038      X(N,2)=1
ISN 0039      150 CONTINUE
C
C      CONSTRUCT REFLECTORS
ISN 0040      IF(SKPRFL.EQ.1)GO TO 163
ISN 0042      DO 160 I=ILX,IUX
ISN 0043      DO 160 K=KLK,KUK
ISN 0044      JW=MBD-K
ISN 0045      NW=NF(I,JW,K)
ISN 0046      X(NW,1)=VRF
ISN 0047      X(NW,2)=1

```

```

ISN 0048      JW = K+MBD
ISN 0049      NW = NF(I,JW,K)
ISN 0050      X(NW,2) = 1
ISN 0051      X(NW,1) = VRF
ISN 0052      160 CONTINUE
ISN 0053      WRITE(M,231) VRF
ISN 0054      231 FORMAT(/1X,'REFLECTOR POTENTIAL = ',1PE15.5)
C
ISN 0055      READ ADDITIONAL FIXED POTENTIALS
ISN 0057      163 IF(NFPS.LE.3)GO TO 220
ISN 0058      118 WRITE(M,118)
                FORMAT(/'ADDITIONAL FIXED POTENTIALS'/
24(6X,'POT',7X,'I',3X,'J',3X,'K' ))
ISN 0059      DO 170 NQC = 1,NFPS,4
ISN 0060      READ(L,119)(VFC(I),IF(I),JF(I),KF(I),I=1,4)
ISN 0061      119 FORMAT(4(E8.0,3I4))
ISN 0062      WRITE(M,117)(VFC(I),IF(I),JF(I),KF(I), I=1,4 )
ISN 0063      117 FORMAT(/4(3X,1PE10.2,3I4))
ISN 0064      165 DO 170 I=1,4
ISN 0065      NN = NF(IF(I),JF(I),KF(I))
ISN 0066      X(NN,1)=VFC(I)
ISN 0067      X(NN,2)=1
ISN 0068      170 CONTINUE
ISN 0069      220 CONTINUE
ISN 0070      IVP=IV+1
ISN 0071      JVP=JV+1
ISN 0072      WRITE(M,113)IIP,IIM,JJP,JJM,KK,IV,JV
ISN 0073      WRITE(M,223) (I,XP(I),I=1,IV)
ISN 0074      WRITE(M,224) (I,XP(I),I=IVP,IIP)
ISN 0075      WRITE(M,225) (I,XM(I),I=1,IIM)
ISN 0076      WRITE(M,226) (J,YP(J),J=1,JV)
ISN 0077      WRITE(M,227) (J,YP(J),J=JVP,JJP)
ISN 0078      WRITE(M,228) (J,YM(J),J=1,JJM)
ISN 0079      WRITE(M,229) (K,ZZ(K),K=1,KK)
ISN 0080      WRITE(M,230) (XP(I),I=1,IV)
ISN 0081      WRITE(M,241)(VP(I),I=1,IV)
C
ISN 0082      111 FORMAT(16I5)
ISN 0083      113 FORMAT(/1X,I3,18H POSITIVE X-VALUES/
1      1X,I3,18H NEGATIVE X-VALUES/
2      1X,I3,18H POSITIVE Y-VALUES/
3      1X,I3,18H NEGATIVE Y-VALUES/
4      1X,I3,25H Z-VALUES (POSITIVE ONLY)/
5      1X,I3,33H POSITIVE X-VALUES DEFINING PANEL/
6      1X, I3,33H POSITIVE Y-VALUES DEFINING PANEL)
ISN 0084      116 FORMAT(8E10.0)
ISN 0085      222 FORMAT(16E5.0)
ISN 0086      223 FORMAT(/1X,27HX-VALUES POSITIVE ON PANEL=/(I3,1PE15.4))
ISN 0087      224 FORMAT(/1X,35HX-VALUES POSITIVE OUTSIDE OF PANEL=/(I3,1PE15.4))
ISN 0088      225 FORMAT(/1X,18HX-VALUES NEGATIVE=/(I3,1PE15.4))
ISN 0089      226 FORMAT(/1X,27HY-VALUES POSITIVE ON PANEL=/(I3,1PE15.4))
ISN 0090      227 FORMAT(/1X,35HY-VALUES POSITIVE OUTSIDE OF PANEL=/(I3,1PE15.4))
ISN 0091      228 FORMAT(/1X,18HY-VALUES NEGATIVE=/(I3,1PE15.4))
ISN 0092      229 FORMAT(/1X,37HZ-VALUES (POSITIVE ONLY) ABOVE PANEL=/(I3,1PE15.4))
ISN 0093      230 FORMAT(/1X,25HARRAY OF PANEL POTENTIALS//
1      15X,3HX =,3X,(8(F8.4,4X)/20X))
ISN 0094      240 FORMAT(/1X,2HYC(I2,2H)=,F8.4,6X,(8(1PE12.4)/20X))
ISN 0095      241 FORMAT(3X,'ALL Y,',5X,(8(1PE12.4)/20X))

```



```

14,15I5)
/1X,34HNPRINT,NPTS,MA,MB,ME,KMAX,PROBNO =,6I6,I10/
NUMBER =, F9.1, 9X,13HTEMPERATURE =, F9.1, 6H VOLTS,9X,
F9.1, 7H PER CC, 9X, 6HMASS =, F9.0,11H ELECTRONS /
11 SCALE =,F9.1,30H METERS = X-DIMENSION OF PANEL)
23HSINGLE SPACE POINT. X =,F10.5,5X, 3HY =,F10.5)
34HSINGLE ENERGY (MONOENERGETIC). E =,F10.5, 6H VOLTS)
27HSINGLE TRAJECTORY. X =,F10.5,5X, 3HY =,F10.5/
11 ALPHA =,F20.8 , 8H DEGREES/
11 BETA =,F20.8 , 8H DEGREES/
RCY =,F20.5, 6H VOLTS)
32HRANDOM THERMAL CURRENT DENSITY =,1PE13.4,
F1 SQUARE METER, FOR,2A5)
11 INTERFACE X-VALUES/(I3,1PE15.4))
18HINTERFACE Y-VALUES/(I3,1PE15.4))
18HINTERFACE Z-VALUES/(I3,1PE15.4))
F22H == CURRENTS AND POWER))

```

II

GO TO 420

I

A5

6

0 TO 480

J

$$Y(1) = Y(6) = -5$$

$$\text{or } Y(11) = 5$$

$$Y(6) = 0$$

I-1)+XX(I))

J-1)+YY(J))

```

ISN 0141      ZK(1)=ZZ(1)
ISN 0142      ZK(KKA)=ZZ(KK)
ISN 0143      DO 560 K=2, KK
ISN 0144      ZK(K)=.5*(ZZ(K-1)+ZZ(K))
ISN 0145      WRITE(M,561) (I,XI(I),I=1,IIA)
ISN 0146      WRITE(M,562) (J,YJ(J),J=1,JJA)
ISN 0147      WRITE(M,563) (K,ZK(K),K=1,KKA)
C
ISN 0148      DO 600 N=1,NTOT
ISN 0149      CALL FINDC(FIND,JFIND,KFIND)
ISN 0150      XYZ(N,1)=XX(FIND)
ISN 0151      XYZ(N,2)=YY(JFIND)
ISN 0152      XYZ(N,3)=ZZ(KFIND)
ISN 0153      600 CONTINUE
C
ISN 0154      IF(SKPLST.EQ.1) GO TO 660
ISN 0155      NFPP=(NTOT/300)+1
ISN 0156      DO 650 IP=1,NFPP
ISN 0157      WRITE(M,9000)
ISN 0158      9000 FORMAT(1H1/6X,1HN,3X,4HX(N),2X,4HY(N),2X,4HZ(N)/)
ISN 0159      CALL LIST(2,IP)
ISN 0160      650 CONTINUE
ISN 0161      660 CONTINUE
C
ISN 0162
ISN 0163      DO 700 J=1,JJ
ISN 0164      DO 700 I=1,II
ISN 0165      N = NF(I,J,1)
ISN 0166      VV(I,J,1) = X(N,1)
ISN 0167      700 CONTINUE
C
ISN 0168      K=1
ISN 0169      WRITE(M,8000) K,ZZ(K),(XX(I),I=1,II)
ISN 0170      DO 750 J=1,JJ
ISN 0171      WRITE(M,240) J,YY(J),(VV(I,J,K),I=1,II)
ISN 0172      750 CONTINUE
C
ISN 0173      CALL FIELD
C
ISN 0174      DO 800 K=1, KK
ISN 0175      DO 800 J=1, JJ
ISN 0176      DO 800 I=1, II
ISN 0177      N=NF(I,J,K)
ISN 0178      VV(I,J,K) = X(N,1)
ISN 0179      800 CONTINUE
C
ISN 0180      DO 900 K=1, KK
ISN 0181      WRITE(M,8000) K,ZZ(K),(XX(I),I=1,II)
ISN 0182      8000 FORMAT(26H1ARRAY OF POTENTIALS AT Z(,I2,2H)=,F8.4//
ISN 0183      1 15X,3HX =,3X,(8(F8.4,4X)/20X))
ISN 0184      DO 850 J=1, JJ
ISN 0185      WRITE(M,240) J,YY(J),(VV(I,J,K),I=1,II)
ISN 0186      850 CONTINUE
ISN 0187      900 CONTINUE
C
ISN 0188      NPROB=0
ISN 0189      1000 READ(L,333,END=99) NPRINT,NPTS,MA,MB,ME,KMAX,MORE
ISN 0190      1001 READ(L,116) SMACH,TVOLTS,DENCC,XMASS,XMETER
ISN 0191      NPROB=NPROB+1

```

ISN 0191	WRITE(M,999)
ISN 0192	WRITE(M,444) NPRINT,NPTS,MA,MB,ME,KMAX,NPROB ,SMACH,TVOLTS,DENCC,
	1 XMASS,XMETER
ISN 0193	IF(NPTS.EQ.0.OR.ME.EQ.0.OR.MA.EQ.0) READ(L,222)XPT,YPT,AL1,BE1,EV
ISN 0195	IF(NPTS.EQ.0) WRITE(M,445) XPT,YPT
ISN 0197	IF(ME.EQ.0) WRITE(M,446) EV
ISN 0199	IF(MA.EQ.0) WRITE(M,447) XPT,YPT,AL1,BE1,EV
ISN 0201	IF(MA.GT.0.AND.XMASS.LE.0.) STOP
ISN 0203	IF(MA.GT.0) CUR=2.68E-8*DENCC*SQRT(ABS(TVOLTS)/XMASS)
ISN 0205	IF(TVOLTS.GT.0.) PARTCL(1)=PART1(1)
ISN 0207	IF(TVOLTS.GT.0.) PARTCL(2)=PART1(2)
ISN 0209	IF(TVOLTS.LT.0.) PARTCL(1)=PART2(1)
ISN 0211	IF(TVOLTS.LT.0.) PARTCL(2)=PART2(2)
ISN 0213	WRITE(M,448) CUR,PARTCL
ISN 0214	CALL POWER
ISN 0215	IF (MORE.GT.0) GO TO 1000
ISN 0217	GO TO 100
ISN 0218	STOP
ISN 0219	END

99

COMPILER OPTIONS = NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

ISN 0002      SUBROUTINE ORBIT
C
C      STEP ACROSS 3-D BOX ASSUMING CONSTANT POTENTIAL WITHIN BOX
ISN 0003      COMMON/8K/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE
ISN 0005      DIMENSION TIME(6),UC(3),UDOT(3),B(2,3)
C
ISN 0006      TOOM=3.3333E+33
ISN 0007      ROUND = 1.E-11
ISN 0008      TROUND = 1.E-6 (5 x 10^-5)
C
ISN 0009      IF(XDOT.EQ.0..AND.YDOT.EQ.0..AND.ZDOT.EQ.0.) WRITE(M,999)
ISN 0011      IF(XDOT.EQ.0..AND.YDOT.EQ.0..AND.ZDOT.EQ.0.) RETURN
ISN 0013      999 FORMAT(1X,38H$SPEED=0 = HENCE PARTICLE DOES NOT MOVE)
C
ISN 0014      U(1)=X
ISN 0015      U(2)=Y
ISN 0016      U(3)=Z
C
ISN 0017      UDOT(1)=XDOT
ISN 0018      UDOT(2)=YDOT
ISN 0019      UDOT(3)=ZDOT
C
ISN 0020      B(1,1)=X1
ISN 0021      B(2,1)=X2
ISN 0022      B(1,2)=Y1
ISN 0023      B(2,2)=Y2
ISN 0024      B(1,3)=Z1
ISN 0025      B(2,3)=Z2
C
ISN 0026      DO 101 N2=1,3
ISN 0027      IF(UDOT(N2).EQ.0.) GO TO 101
ISN 0029      DO 100 N1=1,2
ISN 0030      NR=N1 + 2*(N2-1)
ISN 0031      TIME(NR)=TOOM
ISN 0032      TT=(B(N1,N2) - U(N2))/UDOT(N2)
ISN 0033      SS=U(N2) + UDOT(N2)*TT
ISN 0034      IF(SS.GE.-B(1,N2).AND.SS.LE.B(2,N2)) TIME(NR)=TT
ISN 0036      100 CONTINUE
ISN 0037      101 CONTINUE
C
C      FIND SHORTEST SIGNIFICANT TIME
C
ISN 0038      TIMIN=TOOM
ISN 0039      DO 200 NR=1,6
ISN 0040      IF(TIME(NR).EQ.TOOM) GO TO 200
ISN 0042      IF(TIME(NR).GT.ROUND.AND.TIME(NR).LT.TIMIN) NTIME=NR
ISN 0044      IF(TIME(NR).GT.ROUND.AND.TIME(NR).LT.TIMIN) TIMIN=TIME(NR)
ISN 0046      200 CONTINUE
C
C      ADVANCE TO APPROPRIATE END-POINT

```



$x_2 > x_1$
etc.

what or smallest
if you run the shortest
you'll take the next

$$SS = U(N2) +$$

$$SS = B$$



A8

ISN 0047
ISN 0048
ISN 0049

X=X + XDOT*TIMIN
Y=Y + YDOT*TIMIN
Z=Z + ZDOT*TIMIN

$$X = X + XDOT * (X)$$

C

ISN 0050
ISN 0051
ISN 0052

XSAV=X
YSAV=Y
ZSAV=Z

C

ISN 0053
ISN 0055
ISN 0057
ISN 0059
ISN 0061
ISN 0063

IF(NTIME.EQ.1) X=X1
IF(NTIME.EQ.2) X=X2
IF(NTIME.EQ.3) Y=Y1
IF(NTIME.EQ.4) Y=Y2
IF(NTIME.EQ.5) Z=Z1
IF(NTIME.EQ.6) Z=Z2

C

ISN 0065
ISN 0066
ISN 0067

DX=X-XSAV
DY=Y-YSAV
DZ=Z-ZSAV

C

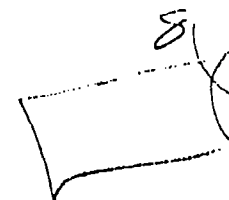
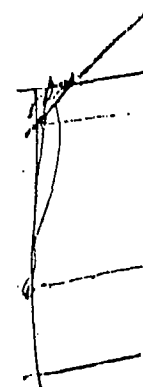
ISN 0068
ISN 0070
ISN 0072
ISN 0074
ISN 0076
ISN 0078

IF((NTIME.EQ.1.OR.NTIME.EQ.2).AND.ABS(DX).GT.TROUND) NTIME=-1
IF((NTIME.EQ.3.OR.NTIME.EQ.4).AND.ABS(DY).GT.TROUND) NTIME=-2
IF((NTIME.EQ.5.OR.NTIME.EQ.6).AND.ABS(DZ).GT.TROUND) NTIME=-3
IF(NTIME.EQ.-1) SAVE=XSAV
IF(NTIME.EQ.-2) SAVE=YSAV
IF(NTIME.EQ.-3) SAVE=ZSAV

C

ISN 0080
ISN 0081

RETURN
END



COMPILER OPTIONS = NAME=,MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

ISN 0002

SUBROUTINE DEN

C
C ROUTINE FOR EVALUATING CURRENT-DENSITY INTEGRALS OVER VELOCITY SPACE

ISN 0003

COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,H,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),

ISN 0004

2XX(40),YY(30),ILX,IUX,KUK,MB,MBD,VRF,NF,PS,SKPRFL,SKPLST
COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,

ISN 0005

1 TVOLTS,CUR,XMETER

ISN 0006

COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)

ISN 0007

COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE

COMMON/INTER/INT,IIA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,

1XI(30),YJ(20),ZK(10)

ISN 0008

DIMENSION AC(2),END1(2),END2(2),FATE(2)

ISN 0009

DATA END1/4HABSO,4HRBED/,END2/4HESCA,4HPES /

ISN 0010

XSAVE=XPT

ISN 0011

YSAVE=YPT

ISN 0012

TEMP=ABS(TVOLTS)

ISN 0013

IF(TEMP.LE.0.) WRITE(M,999) TEMP

ISN 0015

999 FORMAT(/'//1X, 38HTROUBLE = NEGATIVE OR ZERO TEMPERATURE)

ISN 0016

IF(TEMP.LE.0.) RETURN

ISN 0018

IF(MA.EQ.0.OR.ME.EQ.0) EE=EV/TEMP

ISN 0020

PI=3.1415926536

ISN 0021

AC(1)=-1./SQRT(3.)

ISN 0022

AC(2)=-AC(1)

ISN 0023

MSTPS=0

ISN 0024

MSTEP=1000

C
C SET UP SUMS OVER TRAJECTORIES

A10

ISN 0025

IF(MA.EQ.0) GO TO 250

ISN 0027

JAMAX=2

ISN 0028

JBMAX=2

ISN 0029

KAMAX=MA

ISN 0030

KBMAX=MB

ISN 0031

NUMBER=MA*MB*4

ISN 0032

IF(NN.EQ.1) WRITE(M,990) MA,MB,NUMBER

ISN 0034

990 FORMAT(/'1X,I4,16H ALPHA-INTERVALS,3X,I4,15H BETA-INTERVALS,6X,
1 5HENCE,I4,35H TRAJECTORIES FOR EACH ENERGY-VALUE)

C
IF(ME.EQ.0) GO TO 200

ISN 0035

ME2=2*ME

ISN 0037

JEMAX=2

ISN 0038

KEMAX=ME

ISN 0039

IF(NN.EQ.1) WRITE(M,988) ME,ME2

ISN 0040

988 FORMAT(1X,I4,27H ENERGY INTERVALS AND HENCE,I4,14H ENERGY VALUES)

ISN 0042

C
GO TO 300

ISN 0043

C
C SINGLE VALUE OF ENERGY

ISN 0044

200 JEMAX=1

ISN 0045

KEMAX=1

ISN 0046

IF(NN.EQ.1) WRITE(M,986) EV,EE

ISN 0048

986 FORMAT(1X,31H MONOENERGETIC CASE WITH ENERGY,1PE16.4,30H VOLTS, OR
1 DIMENSIONLESS VALUE,E16.4)

ISN 0049

C GO TO 300
C
C SINGLE TRAJECTORY ONLY
C

ISN 0050
ISN 0051
ISN 0052
ISN 0053
ISN 0054
ISN 0055
ISN 0056
ISN 0057
ISN 0058
ISN 0059

250 JAMAX=1
JBMAX=1
JEMAX=1
KAMAX=1
KBMAX=1
KEMAX=1
AL=AL1*PI/180.
BE=BE1*PI/180.
WRITE(M,984) AL1,AL,BE1,BE,EV,EE
984 FORMAT(/1X,17H SINGLE TRAJECTORY
1/1X,7HALPHA =,F20.8,12H DEGREES,OR,F20.8,8H RADIANS
2/1X,7HBETA =,F20.8,12H DEGREES,OR,F20.8,8H RADIANS
3/1X,8HENERGY =,1PE16.4,30H VOLTS,OR DIMENSIONLESS VALUE,E16.4)
SINA=SIN(AL)
COSA=COS(AL)

ISN 0060
ISN 0061

C
C SUM OVER ENERGY, BETA, AND ALPHA
C

ISN 0062
ISN 0063
ISN 0064
ISN 0065
ISN 0066
ISN 0067
ISN 0068
ISN 0069
ISN 0070
ISN 0071

300 CONTINUE
DENS=0.
DO 1001 KE=1,KEMAX
DO 1001 JE=1,JEMAX
DENS=0.
NOESC=0
DO 1000 KB=1,KBMAX
DO 1000 JB=1,JBMAX
DO 1000 KA=1,KAMAX
DO 1000 JA=1,JAMAX

C
C INITIAL POSITION
C

ISN 0072
ISN 0073
ISN 0074
ISN 0075

Z=0.
X=XSAVE
Y=YSAVE
IF(MA.EQ.0) GO TO 320

ISN 0077
ISN 0078
ISN 0079

CA=(A(JA) + FLOAT(2*KA - 1 - MA))/FLOAT(MA)
SINA=SQRT(.5*(1.+CA))
COSA=SQRT(1. - SINA**2)

ISN 0080
ISN 0081

CBETA=(A(JB) + FLOAT(2*KB - 1 - MB))/FLOAT(MB)
BE=PI*(1. + CBETA)

ISN 0082
ISN 0083
ISN 0084
ISN 0085
ISN 0086

C
C
320 XDOT=SINA*COS(BE)
YDOT=SINA*SIN(BE)
ZDOT=COSA
INT=0
CALL INTERP

ISN 0087
ISN 0089

C
IF(IGOUT.GE.1.AND.IGOUT.LE.IIA.AND.JGOUT.GE.1.AND.JGOUT.LE.JJA.
1 AND.KGOUT.GE.1.AND.KGOUT.LE.KKA) GO TO 340
330 WRITE (M,9999)

```

ISN 0090 9999 FORMAT(/////1X,43HONE OF THE IG-JG-KG INDICES IS OUT OF RANGE)
ISN 0091 WRITE (M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0092 WRITE(M,982)KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0093 STOP

C
ISN 0094 340 INT=1
ISN 0095 PHISAV=PHI
ISN 0096 SPEED=0.
ISN 0097 PHIOLD=PHI
ISN 0098 IF(ME.GT.0) GO TO 350

C
ISN 0100 E=EE
ISN 0101 GO TO 400

C
ISN 0102 350 CE=(A(JE) + FLOAT(2*KE-1-ME))/FLOAT(ME)
ISN 0103 E=(1.+CE)/(1.-CE)
ISN 0104 IF(XMACH.GT.1.) E=XMACH**2*(1.+CE)/(1.-CE)
ISN 0106 E=E + AMAX1(PHI, 0.)

C
ISN 0107 400 IF(E.LT.PHI) GO TO 1001
ISN 0109 SPEED=SQRT(E-PHI)

C
ISN 0110 XDOT=SPEED*SINA*COS(BE)
ISN 0111 YDOT=SPEED*SINA*SIN(BE)
ISN 0112 ZDOT=SPEED*COXA
ISN 0113 AL=ARCOS(COSA)
ISN 0114 AL1=AL*180./PI
ISN 0115 BE1=BE*180./PI
ISN 0116 EV=E*TEMP
ISN 0117 PVOLTS=PHISAV*TVOLTS
ISN 0118 ZOLD=Z
ISN 0119 KSTEP=0
ISN 0120 IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 490

C
C PRINT INITIAL CONDITIONS OF TRAJECTORY
C
ISN 0122 WRITE(M,982) KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0123 982 FORMAT(/1X,52HKE,JE, KB,JB, KA,JA, BETA,ALPHA,ENERGY,POTENTIAL=
1, /1X,3(I3,I2),1PE22.8 ,4H DEG,4X,E22.8 ,4H DEG,8X,E16.4,2H V,4X,
2 E16.4,2H V)

C
ISN 0124 WRITE(M,980)
ISN 0125 980 FORMAT( 9X, 95HSTEPS X Y Z XDOT
1 YDOT ZDOT IG JG KG PHI)

C
ISN 0126 WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0127 888 FORMAT( 9X,I5,1P6E11.3,3I6,E11.3)

C
C TAKE A STEP
C
ISN 0128 490 IF (KSTEP.EQ.0) GO TO 550
ISN 0130 500 CALL ORBIT
ISN 0131 KSTEP=KSTEP + 1
ISN 0132 IF(NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
1 JGOUT,KGOUT,PHI
ISN 0134 IF(KSTEP.LE.MSTEP) GO TO 550
ISN 0136 WRITE(M,998) MSTEP
ISN 0137 998 FORMAT(/////1X, 9HMORE THAN,I6,19H STEPS = HENCE STOP)

```


ISN 0138 C STOP
 ISN 0139 C 550 IF(Z.EQ.0..AND.ZDOT.LT.0.
 1.AND.Y.GE.YP(1).AND.Y.LE.YP(JV)) GO TO 600
 ISN 0141 C IF((X.LE.XX(1).AND.ZDOT.LT.0.).OR.
 1(X.GE.XX(II).AND.ZDOT.LT.0.))GO TO 600
 ISN 0143 C IF((X.LE.XX(1).AND.XDOT.LT.0..AND.ZDOT.GT.0.).OR.
 1 (Y.LE.YY(1).AND.YDOT.LT.0.).OR.
 2(X.GE.XX(II).AND.XDOT.GE.0..AND.ZDOT.GT.0.).OR.
 3 (Y.GE.YY(JJ).AND.YDOT.GT.0.).OR.
 4 (Z.GE.ZZ(KK).AND.ZDOT.GT.0.))GO TO 700
 ISN 0145 C IF(SKPRFL.EQ.1) GO TO 538
 ISN 0147 IF((Y.LE.(YY(MBC)+.5*Z)).AND.(Y.GT.(YY(MBC)+.5*ZZ(KUK))))).OR.
 1((Y.GE.(YY(MBD)+.5*Z)).AND.(Y.LT.(YY(MBD)+.5*ZZ(KUK))))
 2.AND.X.GE.XX(ILX).AND.X.LE.XX(IUX)) GO TO 600
 ISN 0149 538 CONTINUE
 ISN 0150 IF (Z.NE.0..OR .ZDOT.GE.0.) GO TO 540
 ISN 0152 ZDOT=-ZDOT
 ISN 0153 IF (NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
 1 JGOUT,KGOUT,PHI
 GO TO 590
 ISN 0155 540 CONTINUE
 ISN 0156 C
 ISN 0157 IF (KSTEP.EQ.0) GO TO 500
 ISN 0159 PHIOLD=PHI
 ISN 0160 CALL INTERP
 ISN 0161 IF(IGOUT.LT.1.OR.IGOUT.GT.IIA.OR.JGOUT.LT.1.OR.JGOUT.GT.JJA.OR.
 1KGOUT.LT.1.OR.KGOUT.GT.KKA) GO TO 330
 IF(NTIME.LT.1.OR.NTIME.GT.6) GO TO 580
 ISN 0163 C
 ISN 0165 IF(NTIME.NE.1.AND.NTIME.NE.2) GO TO 560
 ISN 0167 XDOTS=XDOT**2 + PHIOLD-PHI
 ISN 0168 IF(XDOTS.EQ.0.) XDOT=0.
 ISN 0170 IF(XDOTS.GT.0..AND.XDOT.NE.0.) XDOT=SQRT(XDOTS)*SIGN(1.,XDOT)
 ISN 0172 IF(XDOTS.LT.0..AND.XDOT.NE.0.) XDOT=-XDOT
 ISN 0174 IF(NPRINT.EQ.3.AND.XDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
 1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
 ISN 0176 C 560 IF(NTIME.NE.3.AND.NTIME.NE.4) GO TO 570
 ISN 0178 YDOTS=YDOT**2 + PHIOLD-PHI
 ISN 0179 IF(YDOTS.EQ.0.) YDOT=0.
 ISN 0181 IF(YDOTS.GT.0..AND.YDOT.NE.0.) YDOT=SQRT(YDOTS)*SIGN(1.,YDOT)
 ISN 0183 IF(YDOTS.LT.0..AND.YDOT.NE.0.) YDOT=-YDOT
 ISN 0185 IF(NPRINT.EQ.3.AND.YDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
 1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
 ISN 0187 C 570 IF(NTIME.NE.5.AND.NTIME.NE.6) GO TO 590
 ISN 0189 ZDOTS=ZDOT**2 + PHIOLD-PHI
 ISN 0190 IF(ZDOTS.EQ.0.) ZDOT=0.
 ISN 0192 IF(ZDOTS.GT.0..AND.ZDOT.NE.0.) ZDOT=SQRT(ZDOTS)*SIGN(1.,ZDOT)
 ISN 0194 IF(ZDOTS.LT.0..AND.ZDOT.NE.0.) ZDOT=-ZDOT
 ISN 0196 IF(NPRINT.EQ.3.AND.ZDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
 1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
 ISN 0198 GO TO 590

y < 0 * . S (2) * 1

```

C
ISN 0199 580 WRITE(M,997) NTIME
ISN 0200 997 FORMAT(///1X,17HTROUBLE = NTIME =,I3,19H = OUT OF RANGE 1-6)
ISN 0201 WRITE(M,887) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI,SAVE
ISN 0202 887 FORMAT( 9X,I5,1P6E11.3,3I6,E11.3,'SAVE=',E18.10)
ISN 0203 STOP
C
ISN 0204 590 CALL INTERP
ISN 0205 IF(IGOUT.LT.1.OR.IGOUT.GT.IIA.OR.JGOUT.LT.1.OR.JGOUT.GT.JJA.OR.
1KGOUT.LT.1.OR.KGOUT.GT.KKA) GO TO 330
ISN 0207 IF(NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
1 JGOUT,KGOUT,PHI
ISN 0209 GO TO 500
C
C PARTICLE IS ABSORBED
ISN 0210 600 CONTINUE
ISN 0211 IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 1002
ISN 0213 FATE(1)=END1(1)
ISN 0214 FATE(2)=END1(2)
ISN 0215 GO TO 750
C
C PARTICLE ESCAPES
C
ISN 0216 700 CONTINUE
ISN 0217 IF(NPRINT.EQ.1) GO TO 720
ISN 0219 IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 740
ISN 0221 FATE(1)=END2(1)
ISN 0222 FATE(2)=END2(2)
ISN 0223 GO TO 740
ISN 0224 720 WRITE(M,982) KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0225 740 NOESC=NOESC + 1
ISN 0226 IF(ME.EQ.0) GO TO 750
C
CSANGL=ZDOT/SQRT(XDOT**2+YDOT**2+ZDOT**2)
XPON=-2.*XMACH*SQRT(E)*CSANGL - E - XMACH**2
COEFA=SPEED**2/FLOAT(NUMBER)
ISN 0228 IF(ABS(XPON).GT.36.) GO TO 1000
ISN 0229 ADD =COEFA*EXP(XPON)
ISN 0230 DENS=DENS + ADD
ISN 0231
ISN 0232
ISN 0233
ISN 0234
C
ISN 0235 750 IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 1002
ISN 0237 WRITE(M,889) FATE,KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0238 889 FORMAT(1X,2A4,I5,1P6E11.3,3I6,E11.3)
C
ISN 0239 1002 CONTINUE
ISN 0240 IF(MOSTPS.GE.KSTEP) GO TO 1000
ISN 0242 KES=KE
ISN 0243 JES=JE
ISN 0244 KBS=KB
ISN 0245 JBS=JB
ISN 0246 KAS=KA
ISN 0247 JAS=JA
ISN 0248 MOSTPS=KSTEP
ISN 0249 1000 CONTINUE
C
C END OF SUM OVER ANGLES
C
ISN 0250 FRACT=FLOAT(NOESC)/FLOAT(NUMBER)

```

```

C
ISN 0251 WRITE(M,978) NOESC,NUMBER,FRACT,EV,DENS
ISN 0252 978 FORMAT(/1X,16H RATIO ESCAPING =,I5,7H OUT OF,I5,14H OR A FRACTION,
1 F13.8,14H AT ENERGY E =,F13.8,6H VOLTS,4X,6H(DENS=,1PE14.4,1H))
C
ISN 0253 IF(NPRINT.EQ.0) GO TO 800
ISN 0255 IF(ME.NE.0) WRITE(M,976)
ISN 0257 976 FORMAT(1X,80HDENS IS THE SUM OF ADD=SPEED**2*EXP(XPON)/NUMBER OVER
1 A HEMISPHERE OF DIRECTIONS//)
C
ISN 0258 800 IF(ME.EQ.0) GO TO 1001
ISN 0260 COEFE=2./(1.-CE)**2/FLOAT(ME)
ISN 0261 IF(XMACH.GT.1.) COEFE=COEFE*XMACH**2
ISN 0263 DENST=DENST + COEFE*DENS
ISN 0264 1001 CONTINUE
C
ISN 0265 IF(ME.EQ.0) DENST=SPEED**2*FRACT
C
C TRAJECTORY WITH MOST STEPS. PRINT K AND J INDICES.
C
ISN 0267 WRITE(M,972) MOSTPS,KES,JES,KBS,JBS,KAS,JAS
ISN 0268 972 FORMAT(/1X,I5,3(I3,I2),29H =MOSTPS,KE,JE,KB,JB,KA,JA)
ISN 0269 WRITE(M,974) XSAVE,YSAVE,PHISAV,DENST,PARTCL
ISN 0270 974 FORMAT(/1X,26HAT DIMENSIONLESS X,Y,PHI =,3F12.6,1H,,5X,1PE16.4,
1 33H = NORMALIZED CURRENT DENSITY FOR,2A5//)
ISN 0271 RETURN
ISN 0272 END

```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

ISN 0002      SUBROUTINE INTERP
               C
               C      INTERPOLATION WITHIN GRID
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
               1XYZ(2080,3),VV(30,20,10),XP(30),XMC(10),YP(20),YM(10),ZZ(10),
               2XX(40),YY(30),ILX,IUX,KUK,MBG,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE
ISN 0005      COMMON/INTER/INT,IYA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,
               1XI(30),YJ(20),ZK(10)
               C
ISN 0006      IGOUT=0
ISN 0007      JGOUT=0
ISN 0008      KGOUT=0
ISN 0009      NCH=0
               C
ISN 0010      XA=X
ISN 0011      YA=Y
ISN 0012      ZA=Z
               C
               C      LOCATE XA
ISN 0013      IF(XA.EQ.XI(IIA)) IG=IIA-1
ISN 0015      IF(XA.EQ.XI(IIA)) GO TO 103
ISN 0017      IF(INT.NE.0) GO TO 100
               C
ISN 0019      DO 10 I=2,IIA
ISN 0020      IG=I-1
ISN 0021      IF(XA.LT.XI(I)) GO TO 103
ISN 0023      CONTINUE
A16  ISN 0024      100 IF(XA.GE.XI(IG+1)) GO TO 102
ISN 0026      IF(XA.GE.XI(IG)) GO TO 104
ISN 0028      101 IG=IG-1
ISN 0029      IF(XA.LT.XI(IG)) GO TO 101
ISN 0031      GO TO 103
ISN 0032      102 IG=IG+1
ISN 0033      IF(XA.GE.XI(IG+1)) GO TO 102
               C
ISN 0035      103 NCH=1
ISN 0036      104 CONTINUE
               C
               C      ACCEPT IF XI(IG) LESS THAN OR EQUAL TO XA LESS THAN XI(IG+1).
               C
               C      LOCATE YA
ISN 0037      IF(YA.EQ.YJ(JJA)) JG=JJA-1
ISN 0039      IF(YA.EQ.YJ(JJA)) GO TO 203
ISN 0041      IF(INT.NE.0) GO TO 200
               C
ISN 0043      DO 20 J=2,JJA
ISN 0044      JG=J-1
ISN 0045      IF(YA.LT.YJ(J)) GO TO 203
ISN 0047      20 CONTINUE
               C

```

ISN 0048	200	IF(YA.GE.YJ(JG+1)) GO TO 202
ISN 0050		IF(YA.GE.YJ(JG)) GO TO 204
ISN 0052	201	JG=JG-1
ISN 0053		IF(YA.LT.YJ(JG)) GO TO 201
ISN 0055		GO TO 203
ISN 0056	202	JG=JG+1
ISN 0057		IF(YA.GE.YJ(JG+1)) GO TO 202
	C	
ISN 0059	203	NCH=1
ISN 0060	204	CONTINUE
	C	
	C	ACCEPT IF YJ(JG) LESS THAN OR EQUAL TO YA LESS THAN YJ(JG+1).
	C	
	C	
	C	LOCATE ZA
	C	
ISN 0061		IF(ZA.EQ.ZK(KKA)) KG=KKA-1
ISN 0063		IF(ZA.EQ.ZK(KKA)) GO TO 303
ISN 0065		IF(INT.NE.0) GO TO 300
	C	
ISN 0067		DO 30 K=2,KKA
ISN 0068		KG=K-1
ISN 0069		IF(ZA.LT.ZK(K)) GO TO 303
ISN 0071	30	CONTINUE
	C	
ISN 0072	300	IF(ZA.GE.ZK(KG+1)) GO TO 302
ISN 0074		IF(ZA.GE.ZK(KG)) GO TO 304
ISN 0076	301	KG=KG-1
ISN 0077		IF(ZA.LT.ZK(KG)) GO TO 301
ISN 0079		GO TO 303
ISN 0080	302	KG=KG+1
ISN 0081		IF(ZA.GE.ZK(KG+1)) GO TO 302
	C	
ISN 0083	303	NCH=1
ISN 0084	304	CONTINUE
	C	
	C	ACCEPT IF ZK(KG) LESS THAN OR EQUAL TO ZA LESS THAN ZK(KG+1).
	C	
	C	LOCATE LINE AND BOX
	C	
ISN 0085		X1=XI(IG)
ISN 0086		Y1=YJ(JG)
ISN 0087		Z1=ZK(KG)
ISN 0088		X2=XI(IG+1)
ISN 0089		Y2=YJ(JG+1)
ISN 0090		Z2=ZK(KG+1)
	C	
ISN 0091		IF(X.NE.X1.OR.XDOT.GE.0.) GO TO 400
ISN 0093		IG=IG-1
ISN 0094		X2=X1
ISN 0095		X1=XI(IG)
	C	
ISN 0096	400	IF(Y.NE.Y1.OR.YDOT.GE.0.) GO TO 500
ISN 0098		JG=JG-1
ISN 0099		Y2=Y1
ISN 0100		Y1=YJ(JG)
	C	
ISN 0101	500	IF(Z.NE.Z1.OR.ZDOT.GE.0.) GO TO 600

ISN 0103
ISN 0104
ISN 0105

C
600

ISN 0106
ISN 0107
ISN 0108
ISN 0109
ISN 0110
ISN 0111

KG=KG-1
Z2=Z1
Z1=ZK(KG)
PHI=VV(IG,JG,KG)
IGOUT=IG
JGOUT=JG
KGOUT=KG
RETURN
END

```

ISN 0002      SUBROUTINE POWER
C
C CURRENT DENSITIES AND POWER LOSS
C
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,
                1 TVOLTS,CUR,XMETER
ISN 0005      COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
ISN 0006      DIMENSION A(2)
ISN 0007      IF(NPTS.EQ.0.OR.MA.EQ.0) WRITE(M,997) XPT,YPT,AL1,BE1,EV
ISN 0009      997  FORMAT(/1X, 9HX AND Y =,2F10.5,20X,19HALPHA,BETA,ENERGY =,3F20.5)
ISN 0010      IF(NPRINT.EQ.0) WRITE(M,990)
ISN 0012      IF(NPRINT.EQ.1) WRITE(M,991)
ISN 0014      IF(NPRINT.EQ.2) WRITE(M,992)
ISN 0016      IF(NPRINT.EQ.3) WRITE(M,993)
ISN 0018      990  FORMAT(/38H NPRINT=0 MEANS NO TRAJECTORY PRINTING)
ISN 0019      991  FORMAT(/53H NPRINT=1 PRINT INDICES OF ESCAPING TRAJECTORIES ONLY)
ISN 0020      992  FORMAT(/56H NPRINT=2 PRINT FIRST AND LAST STEPS OF ALL TRAJECTORIE
                1S)
ISN 0021      993  FORMAT(/52H NPRINT=3 MEANS PRINT EVERY STEP OF ALL TRAJECTORIES)
C
ISN 0022      IF(TVOLTS.EQ.0.) RETURN
C
ISN 0024      XMACH=SMACH
C
C NON-DIMENSIONALIZE THE POTENTIAL DISTRIBUTION. THEN RESTORE AT END.
C
ISN 0025      DO 200 K=1,KK
ISN 0026      DO 200 J=1,JJ
ISN 0027      DO 200 I=1,II
ISN 0028      VV(I,J,K)=VV(I,J,K)/TVOLTS
ISN 0029      200  CONTINUE
C
C DEFINE THE PANEL POINTS AT WHICH THE CURRENT AND POWER IS EVALUATED
C
C CASE OF A SINGLE POINT
C
ISN 0030      IF(NPTS.EQ.0.OR.MA.EQ.0) COEFM = XMETER**2
C
C CASE OF MULTIPLE POINTS FOR INTEGRATION OVER PANEL SUB-AREAS
C
ISN 0032      JVM=1
ISN 0033      IVM=1
ISN 0034      IF(JV.GT.1) JVM=JV-1
ISN 0036      IF(IV.GT.1) IVM=IV-1
ISN 0038      NA=0
ISN 0039      NAREAS=IVM*JVM
ISN 0040      IPOWER=0.
ISN 0041      TCURNT=0.
ISN 0042      TAREA=0.
ISN 0043      NN=0
ISN 0044      DO 500 J=1,JVM
ISN 0045      DO 500 I=1,IVM
ISN 0046      NA=NA+1

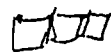
```

```

ISN 0047 NP=0
ISN 0048 IF(NPTS.EQ.0.OR.MA.EQ.0) GO TO 250
ISN 0050 PO = 0
ISN 0051 CU = 0
ISN 0052 A(1)=-1./SQRT(3.)
ISN 0053 A(2)=-A(1)
ISN 0054 GO TO 260
ISN 0055 250 CONTINUE
ISN 0056 JXMAX=1
ISN 0057 JYMAX=1
ISN 0058 KMAX=1
ISN 0059 GO TO 270
ISN 0060 260 JXMAX=2
ISN 0061 JYMAX=2
ISN 0062 270 CONTINUE
ISN 0063 DO 400 KY=1,KMAX
ISN 0064 DO 400 KX=1,KMAX
ISN 0065 DO 400 JY=1,JYMAX
ISN 0066 DO 400 JX=1,JXMAX
ISN 0067 NP=NP+1
ISN 0068 NN=NN+1
ISN 0069 IF(NPTS.EQ.0.OR.MA.EQ.0) GO TO 300
ISN 0070 CX=(A(JX) + FLOAT(2*KX - 1 - KMAX))/FLOAT(KMAX)
ISN 0071 CY=(A(JY) + FLOAT(2*KY - 1 - KMAX))/FLOAT(KMAX)
ISN 0072 XPT=(XP(I+1)-XP(I))/2.*CX + (XP(I+1)+XP(I))/2.
ISN 0073 YPT = (YP(J+1)-YP(J))/2.*CY + (YP(J+1)+YP(J))/2.
ISN 0074 COEF = (XP(I+1)-XP(I))*(YP(J+1)-YP(J))
ISN 0075 AREA = COEF * XMETER**2
ISN 0076 COEFM = AREA/4./FLOAT(KMAX**2)
ISN 0077

```

4x4x4x4x2x



$$LTRJ = NN / (MA \cdot MB \cdot ME \cdot 9)$$

```

C
C COMPUTE EACH CURRENT DENSITY AND MULTIPLY BY LOCAL POTENTIAL TO
C EVALUATE POWER DENSITY
300 CALL DEN

```

$$NIMB2 = \frac{8}{3.2} *$$

```

ISN 0078 DENCUR=DENST*CUR
ISN 0079 POWDEN=PVOLTS*DENCUR
ISN 0080 IF(MA.EQ.0) GO TO 600
ISN 0081 XPTM=XPT*XMETER
ISN 0082 YPTM=YPT*XMETER
ISN 0083 XPM=XP(I)*XMETER
ISN 0084 XPPM=XP(I+1)*XMETER
ISN 0085 YPM=YP(J)*XMETER
ISN 0086 YPPM=YP(J+1)*XMETER
ISN 0087
ISN 0088

```

$$LTRJCT = NN / NIMB$$

```

ISN 0089 995 FORMAT (6X,12HAT POINT NO.,I3,10H, WITH X.=,F10.5,13H METERS, Y =
1,F10.5,27H METERS, AND COEFFICIENT =,F10.5,14H SQUARE METERS)

```

```

ISN 0090 994 IF(NPTS.GT.0.AND.MA.GT.0) WRITE(M,994) NA,XPM,XPPM,YPM,YPPM
ISN 0092 994 FORMAT( /5X,16H IN SUB-AREA NO.,I3,1X,17HBOUNDED BY X IN (,
1 F10.5,3H TO,F10.5, 9H) METERS,,4X,13H AND BY Y IN (,
2 F10.5,3H TO,F10.5, 8H) METERS)

```

```

ISN 0093 988 C WRITE (M,995) NP,XPTM,YPTM,COEFM
ISN 0094 WRITE(M,988) PVOLTS,DENCUR,POWDEN,PARTCL
ISN 0095 988 FORMAT(6X,53H THE VOLTAGE, CURRENT DENSITY, AND POWER DENSITY ARE =
1/6X,1PE16.4,6H VOLTS,4X,E16.4,23H AMP/(SQ-METER), AND,E16.4,
2 24H WATT/(SQ-METER), FOR,2A5//)
ISN 0096 IF(NPTS.EQ.0) GO TO 600

```

A20


```

ISN 0098      CU = CU + COEFM*DENCUR
ISN 0099      PO = PO + COEFM * POWDEN
ISN 0100      400 CONTINUE
ISN 0101      AVCD = CU/AREA
ISN 0102      AVPD = PO/AREA
C
ISN 0103      WRITE(M,986) NA,CU,PO,PARTCL
ISN 0104      WRITE(M,984) NA,AREA,AVCD,AVPD
ISN 0105      984  FORMAT( 1X,18HIN SUB-AREA NUMBER,I3,8H OF AREA,1PE16.4,15H SQUARE
1 METERS,/52H THE AVERAGE CURRENT DENSITY AND POWER DENSITY ARE =,
2 E16.4,19H AMP/(SQ-METER) AND,E16.4,16H WATT/(SQ-METER))
ISN 0106      986  FORMAT( /1X,18HIN SUB-AREA NUMBER,I3,28H THE CURRENT AND POWER ARE
1 =,1PE16.4,12H AMP,      AND,E16.4,14H WATTS,      FOR,2A5)
C
ISN 0107      TAREA=TAREA + AREA
ISN 0108      TCURNT = TCURNT + CU
ISN 0109      TPOWER = TPOWER + PO
ISN 0110      500 CONTINUE
C
ISN 0111      WRITE(M,982) TCURNT,TPOWER,PARTCL
ISN 0112      982  FORMAT(///1X,34HTOTAL CURRENT AND POWER LOSS ARE =,1PE16.4,
1 12H AMP,      AND,E16.4,13H WATT,      FOR,2A5)
ISN 0113      AVCD=TCURNT/TAREA
ISN 0114      AVPD=TPOWER/TAREA
ISN 0115      WRITE(M,980) TAREA,AVCD,AVPD
ISN 0116      980  FORMAT(/1X,26HWITH A TOTAL PANEL AREA OF,1PE16.4,15H SQUARE METERS
1,/1X,51HTHE AVERAGE CURRENT DENSITY AND POWER DENSITY ARE =,
2 E16.4,19H AMP/(SQ-METER) AND,E16.4,16H WATT/(SQ-METER))
C
C
C
C      RESTORE POTENTIAL DISTRIBUTION TO DIMENSIONAL VALUES
C
ISN 0117      600 CONTINUE
ISN 0118      DO 700 K=1,KK
ISN 0119      DO 700 J=1,JJ
ISN 0120      DO 700 I=1,II
ISN 0121      VV(I,J,K)=VV(I,J,K)*TVOLTS
ISN 0122      700 CONTINUE
ISN 0123      RETURN
ISN 0124      END

```

```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002      SUBROUTINE LIST(LST,IP)
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/FLO/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005      DIMENSION KOUT(5),XOUT(5),YOUT(5),ZOUT(5)
ISN 0006      DO 500 LINE=1,60
ISN 0007      DO 200 NP=1,5
ISN 0008      KP=LINE + (NP-1)*60 + (IP-1) * 300
ISN 0009      IF(KP.GT.NTOT.AND.NP.EQ.1) RETURN
ISN 0011      IF(KP.GT. NTOT) GO TO 300
ISN 0013      NMAX=NP
ISN 0014      KOUT(NP) = KP
ISN 0015      IF(LST.EQ.1) XOUT(NP) = X(KP,1)
ISN 0017      IF(LST.EQ. 2) XOUT(NP) =XYZ(KP,1)
ISN 0019      IF(LST.EQ. 2) YOUT(NP)=XYZ(KP,2)
ISN 0021      IF(LST.EQ. 2) ZOUT(NP) =XYZ(KP,3)
ISN 0023      200 CONTINUE
ISN 0024      300 GO TO (400,450),LST
ISN 0025      400 WRITE(M,1000) (KOUT(NP),XOUT(NP), NP=1,NMAX)
ISN 0026      1000 FORMAT(5(I8,F16.8))
ISN 0027      GO TO 500
ISN 0028      450 WRITE(M,3000) (KOUT(NP),XOUT(NP),YOUT(NP),ZOUT(NP),NP=1,NMAX)
ISN 0029      3000 FORMAT(5(I8,3F6.2))
ISN 0030      500 CONTINUE
ISN 0031      RETURN
ISN 0032      END

```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

ISN 0002      SUBROUTINE RELAX
ISN 0003      C      POINT-SUCCESSIVE OVERRELAXATION METHOD
COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCD
ISN 0005      OMEGA=1.9
ISN 0006      EPS = 1.E-3
ISN 0007      ITMAX=2000
ISN 0008      ITR=0
ISN 0009      IPROLD=0
ISN 0010      IGO=1
ISN 0011      200   ITR=ITR+1
ISN 0012      DELTAM=0.
ISN 0013      DO 500 N=1,NTOT
ISN 0014      IF(X(N,2).EQ.1)GO TO 500
ISN 0016      X1=X(N,1)
C
ISN 0017      FN=COEF(N,1)/COEF(N,7)
ISN 0018      FS=COEF(N,2)/COEF(N,7)
ISN 0019      FE=COEF(N,3)/COEF(N,7)
ISN 0020      FW=COEF(N,4)/COEF(N,7)
ISN 0021      FU=COEF(N,5)/COEF(N,7)
ISN 0022      FD=COEF(N,6)/COEF(N,7)
C
ISN 0023      NN=INDX(N,1)
ISN 0024      NS=INDX(N,2)
ISN 0025      NE=INDX(N,3)
ISN 0026      NW=INDX(N,4)
ISN 0027      NU=INDX(N,5)
ISN 0028      ND=INDX(N,6)
C
ISN 0029      SUM=0.
ISN 0030      IF(NN.GT.0) SUM = SUM+FN*X(NN,1)
ISN 0032      IF(NS.GT.0) SUM = SUM+FS*X(NS,1)
ISN 0034      IF(NE.GT.0) SUM = SUM+FE*X(NE,1)
ISN 0036      IF(NW.GT.0) SUM = SUM+FW*X(NW,1)
ISN 0038      IF(ND.GT.0) SUM = SUM+FD*X(ND,1)
ISN 0040      IF(NU.GT.0) SUM = SUM+FU*X(NU,1)
C
ISN 0042      X(N,1) = OMEGA*SUM+(1.-OMEGA)*X1
ISN 0043      DELTA = ABS(X(N,1)-X1)
ISN 0044      IF(ABS(X1).GT.1.E-10) DELTA=ABS((X(N,1)-X1)/X1)
ISN 0046      IF(DELTA .GT. DELTAM) DELTAM=DELTA
ISN 0048      500   CONTINUE
ISN 0049      IF(ITR.GT.ITMAX) WRITE(M,8888) ITR
ISN 0051      IF(ITR.GT.ITMAX) GO TO 700
ISN 0053      8888  FORMAT(///10H MORE THAN, I4,11H ITERATIONS)
ISN 0054      IPR=ITR/500
ISN 0055      IF(IPR.LE.IPROLD) GO TO 600
ISN 0057      IPROLD=IPR
ISN 0058      GO TO 800
C
ISN 0059      600   IF(DELTAM.GT.EPS) GO TO 200
C
C      ITERATION FINISHED. PRINT AND EXIT.

```

ISN 0061	C	
ISN 0062	700	IG0=2
ISN 0063	800	NFPP=(NTOT/300) +1
ISN 0064		DO 900 IP=1,NFPP
ISN 0065	7777	WRITE(M,7777) ITR, EPS, DELTAM, OMEGA
		FORMAT(15H1SOLUTION AFTER, I6, 2X, 25HITERATIONS WITH TOLERANCE,
ISN 0066		1 F12.8, 8X, 18HMAXIMUM DIFFERENCE, F12.8, 8X, 6HOMEGA=, F8.5)
ISN 0067	900	CALL LIST(1, IP)
	C	CONTINUE
ISN 0068		GO TO (600, 1000), I60 IF(160.E4.1) GO TO 600
ISN 0069	1000	RETURN
ISN 0070		END

DATE

LEVEL 21.8 (JUN 74)

OS/360 FORTRAN H

COMPILER OPTIONS - NAME= MAIN,DPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```
ISN 0002      SUBROUTINE FIND(I,J,K)
ISN 0003      COMMON/RK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      IIJJ=II*JJ
ISN 0005      K=N/IIJJ+1
ISN 0006      IF(K .GE. 2 .AND. MOD(N,IIJJ) .EQ. 0) K=K-1
ISN 0008      NKIJ=N - IIJJ*(K-1)
ISN 0009      J=NKIJ/II+1
ISN 0010      IF(J .GE. 2 .AND. MOD(NKIJ,II) .EQ. 0) J=J-1
ISN 0012      I=NKIJ - II*(J-1)
ISN 0013      RETURN
ISN 0014      END
```

```

SUBROUTINE ARRAY
COMMON/IBK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VVC(30,2,10),XPC(30),XC(10),YPC(20),YC(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
COMMON/FLO/X(2080,2),COEFC(2080,7),INDX(2080,6),SKPCO
COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND

```

```

COEFFICIENT ARRAY = COEF(N,7), WHERE
COEF(N,1)=CN (NORTH=+Y NEIGHBOR)
COEF(N,2)=CS (SOUTH=-Y NEIGHBOR)
COEF(N,3)=CE (EAST=+X NEIGHBOR)
COEF(N,4)=CW (WEST=-X NEIGHBOR)
COEF(N,5)=CU (UP=+Z NEIGHBOR)
COEF(N,6)=CD (DOWN=-Z NEIGHBOR)
COEF(N,7)=CC ( = CENTRAL POINT)

```

ISN	0006
ISN	0007
ISN	0008
ISN	0009
ISN	0010
ISN	0011
ISN	0012

```
COEF(N,1)=CN
COEF(N,2)=CS
COEF(N,3)=CE
COEF(N,4)=CW
COEF(N,5)=CU
COEF(N,6)=CD
COEF(N,7)=CC
```

ISBN	0013
ISBN	0014
ISBN	0015
ISBN	0016
ISBN	0017
ISBN	0018

```

INDX(N,1)=NN
INDX(N,2)=NS
INDX(N,3)=NE
INDX(N,4)=NW
INDX(N,5)=NU
INDX(N,6)=ND

```

ISBN	0019
ISBN	0021
ISBN	0022
ISBN	0023
ISBN	0024
ISBN	0025

```
IF(SKPCO.EQ.1) GO TO 20
WRITE(M,1000) ND,CO,NS,CS,NW,CW,N,CC,NE,CE,NN,CN,NU,CU
FORMAT(7(1X,1H(,1A,2H)=,1PE10.4))
CONTINUE
RETURN
END
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

ISN 0002      SUBROUTINE CUD(MP,C,A)
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                2XX(40),YY(30),ILX,IUX,KUK,MBC,M8D,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
ISN 0005      NF(IX,JX,KX) = IX+II*(JX-1) + II*JJ*(KX-1)
ISN 0006      A=0.
ISN 0007      C=0.
ISN 0008      CALL FIND(I,J,K)
ISN 0009      IF(I.EQ. 1) GO TO 100
ISN 0011      IF(I.EQ. II) GO TO 200
ISN 0013      NH=NF(I+1,J,K)
ISN 0014      NL=NF(I-1,J,K)
ISN 0015      DX=XYZ(NH,1) - XYZ(NL,1)
ISN 0016      GO TO 300
ISN 0017      100 NH=NF(2,J,K)
ISN 0018      DX=XYZ(NH,1) - XYZ(N,1)
ISN 0019      GO TO 300
ISN 0020      200 NL=NF(II-1,J,K)
ISN 0021      DX=XYZ(N,1) - XYZ(NL,1)
ISN 0022      300 CONTINUE
ISN 0023      IF(J.EQ. 1) GO TO 400
ISN 0025      IF(J.EQ. JJ) GO TO 500
ISN 0027      NH=NF(I,J+1,K)
ISN 0028      NL=NF(I,J-1,K)
ISN 0029      DY=XYZ(NH,2) - XYZ(NL,2)
ISN 0030      GO TO 600
ISN 0031      400 NH=NF(I,2,K)
ISN 0032      DY=XYZ(NH,2) - XYZ(N,2)
ISN 0033      GO TO 600
ISN 0034      500 NL=NF(I,JJ-1,K)
ISN 0035      DY=XYZ(N,2) - XYZ(NL,2)
ISN 0036      600 A=DX*DY/4.
ISN 0037      IF(MP.EQ. 1) GO TO 700
ISN 0039      IF(MP.EQ. 2) GO TO 800
ISN 0041      RETURN
ISN 0042      700 NU=0
ISN 0043      IF(K.EQ. KK) RETURN
ISN 0045      NH=NF(I,J,K+1)
ISN 0046      NU=NH
ISN 0047      DZ=XYZ(NH,3) - XYZ(N,3)
ISN 0048      GO TO 900
ISN 0049      800 ND=0
ISN 0050      IF(K.EQ. 1) RETURN
ISN 0052      NL=NF(I,J,K-1)
ISN 0053      ND=NL
ISN 0054      DZ=XYZ(N,3) - XYZ(NL,3)
ISN 0055      900 C=A/DZ
ISN 0056      RETURN
ISN 0057      END

```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

```

1SN 0002      SUBROUTINE CNS(MP,C,A)
1SN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),Y(30),ILX,IUX,KUK,MBK,MBD,VRF,NFPS,SKPRFL,SKPLST
      COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,NO
      NF(IX,JX,KX)=IX+II*(JX-1)+II*JJ*(KX-1)
      A=0.
      C=0.
      CALL FIND(I,J,K)
      IF(I.EQ.1) GO TO 100
      IF(I.EQ.II) GO TO 200
      NH=NF(I+1,J,K)
      NL=NF(I-1,J,K)
      DX=XYZ(NH,1) - XYZ(NL,1)
      GO TO 300
100      NH=NF(2,J,K)
      DX=XYZ(NH,1) - XYZ(N,1)
      GO TO 300
200      NL=NF(II-1,J,K)
      DX=XYZ(N,1) - XYZ(NL,1)
300      CONTINUE
      IF(K.EQ.1) GO TO 400
      IF(K.EQ.KK) GO TO 500
      NH=NF(I,J,K+1)
      NL=NF(I,J,K-1)
      DZ=XYZ(NH,3) - XYZ(NL,3)
      GO TO 600
400      NH=NF(I,J,2)
      DZ=XYZ(NH,3) - XYZ(N,3)
      GO TO 600
500      NL=NF(I,J,KK-1)
      DZ=XYZ(N,3) - XYZ(NL,3)
      A=DX*DZ/4.
      IF(MP.EQ.1) GO TO 700
      IF(MP.EQ.2) GO TO 800
      RETURN
      NN=0
700      IF(J.EQ.JJ) RETURN
      NH=NF(I,J+1,K)
      NN=NH
      DY=XYZ(NH,2) - XYZ(N,2)
      GO TO 900
800      NS=0
      IF(J.EQ.1) RETURN
      NL=NF(I,J-1,K)
      NS=NL
      DY=XYZ(N,2) - XYZ(NL,2)
900      C=A/DY
      RETURN
      END

```


COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NODEIT,NOID,NOXREF

```

ISN 0002      SUBROUTINE CEW(CP,C,A)
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBC,MBO,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
ISN 0005      NF(IX,JX,KX)= IX+ II*(JX-1) + II*JJ*(KX-1)
ISN 0006      A=0.
ISN 0007      C=0.
ISN 0008      CALL FIND(I,J,K)
ISN 0009      IF(J.EQ.1) GO TO 100
ISN 0011      IF(J.EQ. JJ) GO TO 200
ISN 0013      NH=NF(I,J+1,K)
ISN 0014      NL=NF(I,J-1,K)
ISN 0015      DY=XYZ(NH,2) - XYZ(NL,2)
ISN 0016      GO TO 300
ISN 0017      100 NH=NF(I,2,K)
ISN 0018      DY=XYZ(NH,2) - XYZ(N,2)
ISN 0019      GO TO 300
ISN 0020      200 NL=NF(I,JJ-1,K)
ISN 0021      DY=XYZ(N,2) - XYZ(NL,2)
ISN 0022      300 CONTINUE
ISN 0023      IF(K.EQ. 1) GO TO 400
ISN 0025      IF(K.EQ. KK) GO TO 500
ISN 0027      NH=NF(I,J,K+1)
ISN 0028      NL=NF(I,J,K-1)
ISN 0029      DZ=XYZ(NH,3) - XYZ(NL,3)
ISN 0030      GO TO 600
ISN 0031      400 NH=NF(I,J,2)
ISN 0032      DZ=XYZ(NH,3) - XYZ(N,3)
ISN 0033      GO TO 600
ISN 0034      500 NL=NF(I,J,KK-1)
ISN 0035      DZ=XYZ(N,3) - XYZ(NL,3)
ISN 0036      600 A=DY*DZ/4.
ISN 0037      IF(CP.EQ. 1) GO TO 700
ISN 0039      IF(CP.EQ. 2) GO TO 800
ISN 0041      RETURN
ISN 0042      700 NE=0
ISN 0043      IF(I.EQ.II) RETURN
ISN 0045      NH=NF(I+1,J,K)
ISN 0046      NE=NH
ISN 0047      DX=XYZ(NH,1) - XYZ(N,1)
ISN 0048      GO TO 900
ISN 0049      800 NW=0
ISN 0050      IF(I.EQ. 1) RETURN
ISN 0052      NL=NF(I-1,J,K)
ISN 0053      NW=NL
ISN 0054      DX=XYZ(N,1) - XYZ(NL,1)
ISN 0055      900 C=A/DX
ISN 0056      RETURN
ISN 0057      END

```

COMPILER OPTIONS = NAME= MAIN,DPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

DATE

```

ISN 0002      SUBROUTINE FIELD
C
C      CONSTRUCTION OF COEFFICIENTS (MATRIX ELEMENTS)
C      IN LINEAR DIFFERENCE EQUATIONS
C      SOLUTION BY OVERRELAXATION
ISN 0003      COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
1XYZ(2080,3),VV(30,20,10),XP(30),XMC(10),YP(20),YMC(10),ZZ(10),
2XX(40),YY(30),ILX,IUX,KUK,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004      COMMON/FLO/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005      COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
C
ISN 0006      INTEGER OO,ON/'NORT'/,OS/'SOUT'/,OE/'EAST'/,OW/'WEST'/,
1OU/'UP'/'/,OD/'DOWN'/'
C      ASSUME ASYMPTOTIC MONOPOLE AT INFINITY
C
ISN 0007      ALPHAF(UUU)=ABS(UUU/RS)
C
C      NDO=POSITIVE FOR DIAGNOSTIC OUTPUT
ISN 0008      NDO=0
C
ISN 0009      WRITE(M,1000)
ISN 0010      1000 FORMAT(1H1/18HOFIELD CALCULATION)
ISN 0011      WRITE(M,2000)
ISN 0012      2000 FORMAT(///1X,17HCOEFFICIENT ARRAY)
ISN 0013      X0=.5*XP(IV)
ISN 0014      Y0=.5*YP(JV)
ISN 0015      ZOLD=0.
ISN 0016      DO 600 N=1,NTOT
ISN 0017      RS=(XYZ(N,1)-X0)**2 +(XYZ(N,2)-Y0)**2 +XYZ(N,3)**2
ISN 0018      CALL FIND (1,J,K)
ISN 0019      IF(ZZ(K).LE.ZOLD.AND.N.GT.1) GO TO 200
ISN 0021      ZOLD=ZZ(K)
ISN 0022      WRITE(M,3000) K,ZZ(K)
ISN 0023      3000 FORMAT( //1X,2HZ(,I2,2H)=,F6.3/
1 12X,1HD,17X,1HS,17X,1HW,17X,1HC,17X,1HE,17X,1HN,17X,1HU)
ISN 0024      200 CC=0.
C
C      MODIFICATION TO SOLVE HELMHOLTZ EQUATION USING LINEARIZED SPACE
C      CHARGE. HELM = DEBYE-LENGTH-LIKE PARAMETER. (ASSUMES POTEN-
C      TIALS ARE DIMENSIONLESS)
C
ISN 0025      HELM=0.0
ISN 0026      VOLSO=1.
ISN 0027      DO 300 MP=1,2
ISN 0028      CALL CNS(MP,C,AREA)
ISN 0029      IF (MP.EQ.1) OO=ON
ISN 0031      IF (MP.EQ.2) OO=OS
ISN 0033      IF (NDO.GT.0) WRITE (M,888) N,I,J,K,OO,AREA,C
ISN 0035      888 FORMAT(1X,18HN,I,J,K,OO,AREA,C=,I4,2X,3I3,1X,A5,1P2E16.4)
ISN 0036      CC=CC+C
ISN 0037      IF(C.GT.0.) GO TO 250
ISN 0039      YYY=XYZ(N,2)-Y0
ISN 0040      ALPHA=ALPHAF(YYY)
ISN 0041      IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0043      999 FORMAT(1X,14HN,I,J,K,ALPHA=,I4,2X,3I3,1PE16.4)

```

```

ISN 0044      CC=CC+AREA*ALPHA*(YYY)
ISN 0045      250 IF(MP.EQ.1) CN=C
ISN 0047      IF(MP.EQ.2) CS=C
ISN 0049      300 CONTINUE
ISN 0050      VOLSQ=VOLSQ*AREA
ISN 0051      DO 400 MP=1,2
ISN 0052      CALL CEW(MP,C,AREA)
ISN 0053      IF (MP.EQ.1) DO=OE
ISN 0055      IF (MP.EQ.2) DO=OW
ISN 0057      IF (NDO.GT.0) WRITE (M,888) N,I,J,K,DO,AREA,C
ISN 0059      CC=CC+C
ISN 0060      IF(C.GT.0.) GO TO 350
ISN 0062      XXX=XYZ(N,1)-XO
ISN 0063      ALPHA=ALPHA*(XXX)
ISN 0064      IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0066      CC=CC+AREA*ALPHA*(XXX)
ISN 0067      350 IF(MP.EQ.1) CE=C
ISN 0069      IF(MP.EQ.2) CW=C
ISN 0071      400 CONTINUE
ISN 0072      VOLSQ=VOLSQ*AREA
ISN 0073      DO 500 MP=1,2
ISN 0074      CALL CUD(MP,C,AREA)
ISN 0075      IF (MP.EQ.1) DO=OU
ISN 0077      IF (MP.EQ.2) DO=OD
ISN 0079      IF (NDO.GT.0) WRITE (M,888) N,I,J,K,DO,AREA,C
ISN 0081      CC=CC+C
ISN 0082      IF(C.GT.0..OR.(C.EQ.0..AND.MP.EQ.2))GO TO 450
ISN 0084      ALPHA=ALPHA*(XYZ(N,3))
ISN 0085      IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0087      CC=CC+AREA*ALPHA*(XYZ(N,3))
ISN 0088      450 IF(MP.EQ.1) CU=C
ISN 0090      IF(MP.EQ.2) CD=C
ISN 0092      500 CONTINUE
ISN 0093      VOLSQ=VOLSQ*AREA
ISN 0094      VOL=SQRT(VOLSQ)
ISN 0095      IF(HELM.GT.0.) CC=CC+VOL/HELM**2
ISN 0097      CALL ARRAY
ISN 0098      600 CUNTINUE
C
ISN 0099      CALL RELAX
ISN 0100      RETURN
ISN 0101      END

```

US/360 FORTRAN H

DATE

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=60,SIZE=0000K,
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF

ISN 0002
ISN 0003
ISN 0004
ISN 0005

BLOCK DATA
COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
REAL PART1/'IONS',',',',',PART2/'ELEC',',',TRON',/
END

Appendix B

Computer Programs: Electric Fields Produced by Cloud-to-Ground Lightning Flashes

The following four pages contain a listing of the computer programs written to compute the electric field produced on the ground as a function of time and distance from "ground zero" by the charges associated with a cloud-to-ground lightning flash. This program was written by Jerry L. Bohannon.


```

81  FORMAT(2F10.0)
90  VSL=VSL
   RSI(1.10)=RSI(1.9)
   DO 1002 J=1.10
   RSI(1.J)=RSI(1.J)
   RSI(2.J)=RSI(2.J)
   RSI(1.J)=RSI(1.J)/1000.
   RSI(2.J)=RSI(2.J)*1000.
1002 CONTINUE
   QCL=-QCL
   QSL=-QSL
   YOS=Y0
   RAD=(0.75*ABS(QCL)/RHO/PIE)**CROOT
   DO 1005 I=2.9
   A=RSI(2.I)
   B=RSI(2.I-1)
   C=RSI(2.I+1)
   IF(A.GT.B.AND.A.GT.C) IQT=I
1005 CONTINUE
   VRSS=VRS
100  VSL=-VSL*1.0E5
   YO=Y0*1000.0
   VRS=VRS*1.0E7
   DTS=1.0E-4
105  WRITE(14,110) IBL,ICY
110  FORMAT(A2,"WHAT IS RADIUS",A2)
   READ(15,73) D
   WRITE(13,111) IRD,IBGY
111  FORMAT(2A2,"")
   DO 1001 I=1.32000
   1001 K=I
   WRITE(13,149)
   149 FORMAT(1X,"S:I UNITS"/)
   150 WRITE(13,151) YOS,QCL,QSL,VSL,VRSS,RSI(1.10)
151  FORMAT(1X,"HEIGHT=","F7.10," KM/1X,"Q-CLOUD=","F7.1," C"/
   $1X,"Q-LEADER=","F6.1," C"/1X,"V-LEADER=","F6.1," E5 M/S"/1X,
   $ "V-RETURN=","F6.1," E7 M/S"/1X,"RETURN STROKE MS. KAMP"/
   $1X(2F10.4)/1X,"RADIUS=","F6.0," M"/)
   WRITE(13,152) IRG,IRD
52  FORMAT(1X,
   $A2.8X,"T",15X,"E",15X,"Q",16X,"H",A2)
   T=0.0
   SLRY2=1.0/(D*D+Y0*Y0)
   SLRY=SQRT(SLRY2)
   YC=Y0+RAD
   SLRQC2=1.0/(D*D+YC*YC)
   SLRQCL=SQRT(SLRQC2)*SLRQC2
   DI=1.0/D
   X=Y0
   EMAX=0.0
00  CONTINUE
   SLRX2=1.0/(D*D+X*X)
   SLRX=SQRT(SLRX2)
   SLRX32=SLRX*SLRX2
   E=QSL/PIE/Y0*(SLRX-SLRY)*SLRQCL*YC/PIE*(QCL-QSL*(1.-X/Y0))
   IF(ABS(E).GT.ABS(EMAX)) EMAX=E
   IF(ABS(E).LT.5.0E4) GOTO 211
   WRITE(13,210) T,E,X
10  FORMAT(F16.7,F16.0,16X,F16.1)

```

```

215  FORMAT(F16.7,F16.0,F16.5,F16.1,I10,F16.7,F16.0)
211  IF(ABS(E).LT.5.0E4.OR.X.GT.0.5E3) DTSL=1.0E-3
      T=T+DTSL
      IF(X.LT.50.) GOTO 500
      X=Y0+VSL*T
      IF(X.LT.0.0) GOTO 500
      DTSL=1.0E-4
      GOTO 200
500  CONTINUE
      T=T-DTSL
      WRITE(13,501)
501  FORMAT(1X,'  ')
      ESL=E
      QRC=QSL-QCL
      PL=-QSL/Y0
      SLRY03=YC*SLRQCL
      KRNT=1
      RI=0.0
      TR=0.0
      KOLD=0
      Q=0.0
510  CONTINUE
      CALL CURENT(IRSI,Q,DT,TR,IRI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      Y=VRS+TR
      IF(Y.GT.Y0) GOTO 522
      P=Q/Y
      SLRYR=1.0/SQRT(D+D+Y*Y)
      E=ESL+P*(DI-SLRYR)/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(1QT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 510
      WRITE(13,215) T,E,Q,Y,KRNT,TR,RI
      GOTO 510
22  WRITE(13,501)
20  CONTINUE
      P=Q/Y0
      IF(P.GT.PL) GOTO 572
      E=ESL+P*(DI-SLRY)/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(1QT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 521
      WRITE(13,215) T,E,Q,Y0,KRNT,TR,RI
21  CALL CURENT(IRSI,Q,DT,TR,IRI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      GOTO 520
72  WRITE(13,501)
70  CONTINUE
      QRS=Q+QSL
      IF(QRS.GT.QRC) GOTO 600
      E=ESL+PL*(DI-SLRY)/TPIE+QRS*SLRY03/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(1QT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 571
      WRITE(13,215) T,E,Q,YC,KRNT,TR,RI
71  CALL CURENT(IRSI,Q,DT,TR,IRI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      GOTO 570
0  WRITE(13,599) Q,EMAX

```



```

99  FORMAT(//1X,"QRT= ",F10.4," CT=5X,"EMAX= ",E12.4," V/M")
    WRITE(14,601) IBG,IBL,IGR,IBEL
101  FORMAT(2A2," DO YOU WANT ANOTHER RADIOUS",2A2)
102  READ(15,12) IAD
    IF(IAD.EQ.1Y) GOTO 105
    IF(IAD.EQ.1N) GOTO 650
    WRITE(14,14) IRD,IGR
    GOTO 602
105  WRITE(14,651) IBL,IGR
106  FORMAT(2A2," DO YOU WANT ANOTHER EVENT",2A2)
107  READ(15,12) IE
    IF(IE.EQ.1Y) GOTO 13
    IF(IE.EQ.1N) GOTO 950
    WRITE(14,14) IRD,IGR
    GOTO 652
108  WRITE(14,998) IRD
109  FORMAT(2A2," NO MORE CARDS")
110  WRITE(14,951) IMA,IGR
111  FORMAT(2A2," END OF PROGRAM",2A2)
    STOP 1
    END
LAB= CURENT
DBG
SUBROUTINE CURENT(RSI,Q,DT,TR,RI,KRNT,KOLD)
  IMPLICIT INTEGER*2 (I-N)
  DIMENSION RSI(2,10)
  IF(KOLD.EQ.KRNT) GOTO 50
  TAU=RSI(1,KRNT+1)-RSI(1,KRNT)
  IF(TAU.LE.0.) GOTO 100
  IF(TAU.LE.1.E-5) DT=0.5E-6
  IF(TAU.GT.1.E-5.AND.TAU.LE.1.E-4) DT=1.E-5
  IF(TAU.GT.1.E-4.AND.TAU.LE.1.E-3) DT=1.E-4
  IF(TAU.GT.1.E-3.AND.TAU.LE.1.E-2) DT=1.E-3
  IF(TAU.GT.1.E-2.AND.TAU.LE.1.E-1) DT=1.E-2
  IF(TAU.GT.1.E-1) DT=0.025
  DELI=(RSI(2,KRNT+1)-RSI(2,KRNT))/TAU
  IF(Q.EQ.0.0) RI=0.0
  TR=TR+DT
  IF(TR.GT.RSI(1,KRNT+1)) CT=RSI(1,KRNT+1)-TR
  RI=RI+DELI*DT
  RI2=RI
  Q=Q+DT*(RI2+RI)/2.
  TR=TR+DT
  KOLD=KRNT
  IF(TR.GE.RSI(1,KRNT+1)) KRNT=KRNT+1
  RI=RI2
  RETURN
10  CONTINUE
  RI=0.0
  RETURN
  END
11  END

```

Appendix C

Computer Output Listing: Cloud-to-Ground Lightning Flash Density

The following seven pages are the computed output from the program that calculates the lightning flash density (cloud-to-ground) from the monthly thunderstorm days using the Pierce Conversion. This program, written by Jerry L. Bohannon, uses the Normals, Means and Extremes data from "Local Climatological Data -- Annual Summaries for 1977" published by the National Oceanic and Atmospheric Administration, Environmental Data Service, Asheville, North Carolina (available also on magnetic tape).

```

7COMPUPOT [5]7
V AAR←WID COMPUPOT HI
[11] A THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL IN A REGION AROUND
[21] A ONE BILLBOARD OF THE RECTENNA, THE MEASUREMENT AREA STARTS 31.96 METERS
[31] A FROM THE LEFT HAND EDGE OF THE RECTENNA AND EXTENDS TO THE RIGHT 'AC' METERS,
[41] A THE BOTTOM OF THE MEASUREMENT AREA IS AT GROUND LEVEL, WHILE THE TOP
[51] A IS 'UP' METERS HIGH,
[61] A THE RESOLUTION IS CONTROLLED BY THE ARGUMENTS OF THE FUNCTION, THE
[71] A LEFT ARGUMENT SPECIFIES THE NUMBER OF COLUMNS IN THE OUTPUT, THE RIGHT
[81] A ARGUMENT IS THE NUMBER OF ROWS,
[91] A THE FORMAT OF THE OUTPUT IS AN ARRAY OF NUMBERS IN SCIENTIFIC NOTATION
[101] A WITH ONLY ONE SIGNIFICANT DIGIT PRINTED,
[111] POT←(HI,WID)P0
[121] QPF←1
[131] R←R+1
[141] LOOPH;H1←(Q-1)XUP+HI-1
[151] R←1
[161] LOOPL;L1←31.96+(R-1)XAC+WID-1
[171] POT[R;R]←L1 FIELD H1
[181] R←R+1
[191] A←(R(WID)/LOOPL
[201] Q←Q+1
[211] A←(Q(HI)/LOOPH
[221] TRY←TRY+1
[231] DATE←1#3#QTS.
[241] 'THIS IS RUN NUMBER ',(TRY),DATE
[251] 'THE CALCULATED VALUES OF THE ELECTRIC POTENTIAL, IN VOLTS, ARE SHOWN BELOW,'
[261] ''
[271] ''
[281] AAR←POT←SPOT
[291] SPDAVE[201]←
[301] QPF←10
[311] 'THE VECTOR OF LINE CHARGES USED IS,,,',(LA),' COULOMBS PER METER,'
[321] 'THE SUM OF THE LINE CHARGES IS ',(+/LA),' COULOMBS PER METER,'
[331] 'THE TOP OF THE MEASUREMENT ARRAY IS ',(UP),' METERS HIGH,'
[341] 'THE RIGHT EDGE OF THE ARRAY IS ',(L1),' METERS FROM THE FIRST BILLBOARD,'
[351] 'THERE ARE ',(AC+WID),' COLUMNS PER METER, AND ',(UP+HI),' ROWS PER METER ON THE ARRAY,'
[361] 'RUN NO. ',(TRY),DATE
[371] QPF←1
[381] SPDAVE[201]
[391] A←(SIGN=0)/0
[401] 'THE ARRAY BELOW SHOWS THE SIGN OF EACH OF THE NUMBERS IN THE ABOVE ARRAY,'
[411] ''
[421] XPOT
[431] 'THIS IS RUN NUMBER ',(TRY),DATE
7

```

```

9PROTECT [0]V
9 WID PROTECT HI
[1] A THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL IN A REGION OF SPACE
[2] A DUE TO A CHARGED WIRE LOCATED SOME FIXED PERPENDICULAR DISTANCE FROM
[3] A THE TOP OF EACH BILLBOARD OF THE RECTENNA, THE MEASUREMENT AREA IS
[4] A EXACTLY THE SAME AS THAT USED IN ((COMPUPOT)), AS WITH ((COMPUPOT))
[5] A THE RESOLUTION IS DETERMINED BY THE ARGUMENTS OF THE FUNCTION,
[6] A THE FUNCTION DOES NOT PRINT ANY OUTPUT, THE OUTPUT IS CONTAINED IN
[7] A THE VARIABLE, ((PROT)), THIS VARIABLE WILL HAVE THE SAME DIMENSIONS AS
[8] A ((POT)), THE VARIABLE CONTAINING THE OUTPUT FROM ((COMPUPOT)),
[9] PROT=(HI,WID)*0
[10] Q1=Q1+1
[11] A ((LOOPH)) COMPUTES ALL OF THE VERTICAL INDICES,
[12] LOOPH:H2+(Q1-1)*UP:HI-1
[13] R1=1
[14] A ((LOOPL)) COMPUTES THE HORIZONTAL INDICES AND CALLS ((FIELDW)),
[15] LOOPL:L2+J1,96+(R1-1)*AC:WID-1
[16] PROT[Q1;R1]=L2 FIELDW H2
[17] R1=R1+1
[18] +(R1*WID)/LOOPL
[19] Q1=Q1+1
[20] +(Q1*HI)/LOOPH
[21] PROT=PROT
[22] TRY1=TRY1+1
[23] 'THIS IS RUN NUMBER ',(TRY1),' OF PROTECT',DATE
[24] DPP=10
[25] 'THE PROTECTING WIRE IS LOCATED ',(XJ1),' METERS FROM THE'
[26] 'LEFT EDGE OF THE ARRAY, AND ',(S1*XJ1),' METERS FROM THE BOTTOM,'
9

```

```

VFIELD [0]
V UHL=L FIELD H
[1]  THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL AT ANY POINT, (L,H)
[2]  IN THE SPACE AROUND THE ARRAY OF FIVE BILLBOARDS,
[3]  LI=15.93x-1+1H
[4]  XJ=(9.38x(N)+NA)/LA
[5]  S=3002+9
[6]  A=L-XJ
[7]  I=1
[8]  UI=M/0
[9]  BBLOOP;NM=((H-SxXJ)x2)+NA+(A-LI[I])x2
[10]  DM=((H+SxXJ)x2)+NA
[11]  UI[I]=+/-((LA+S2xEO)x(NM+DM)x0.5
[12]  I=I+1
[13]  +(I(N+1))/BBLOOP
[14]  UHL=(-100000xH)++/UI
V

```

```

VFIELDW [0]
V P=L FIELDW H
[1]  THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL AT ANY POINT, (L,H),
[2]  DUE TO THE CHARGED PROTECTION WIRE ABOVE THE BILLBOARD, THIS WIRE IS
[3]  ASSUMED TO BE PARALLEL TO THE BILLBOARD AND LOCATED A PERPENDICULAR
[4]  DISTANCE, ((SPACE)), FROM THE TOP OF THE BILLBOARD,
[5]  THE CHARGE ON THE WIRE IS ((LW)),
[6]  LI=15.93x-1+1H
[7]  M=LW/LA
[8]  LONG=12.24+23THTA+30(+12.24)xSPACE
[9]  XJ1=XJ1+LONGx20THTA+S2+9
[10]  S1=30(02+9)+THTA
[11]  A1=L-XJ1
[12]  I=1
[13]  UI1=M/0
[14]  LBSP;NM1=((H-S1xXJ1)x2)+NA1+(A1-LI1[I])x2
[15]  DM1=((H+S1xXJ1)x2)+NA1
[16]  UI1[I]=+/-((LW+S2xEO)x(NM1+DM1)x0.5
[17]  I=I+1
[18]  +(I(N+1))/LBSP
[19]  P1=+/UI1
V

```

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND STRIKE DENSITY (NO./YR./KM ²)
AL	BIRMINGHAM	53.71	13.87
AL	HUNTSVILLE	59.20	13.34
AL	MOBILE	79.78	27.07
AL	MONTGOMERY	62.13	15.44
AK	ANCHORAGE	1.12	0.39
AK	ANNETTE	1.43	0.50
AK	BARROW	0.07	0.06
AK	BARTER ISLAND	0.26	0.17
AK	BETHEL	1.39	0.51
AK	BETTLES	4.67	0.78
AK	BIG DELTA	2.50	0.41
AK	COLD BAY	0.05	0.04
AK	FAIRBANKS	5.12	0.83
AK	GULKANA	4.70	0.76
AK	HOMER	0.38	0.15
AK	JUNEAU	0.32	0.24
AK	KING SALMON	1.31	0.48
AK	KODIAK	0.29	0.09
AK	KOTZEBUE	0.52	0.24
AK	MC GRATH	6.77	1.05
AK	NOOME	0.42	0.19
AK	ST PAUL ISLAND	0.05	0.05
AK	SHEYMA ISLAND	0.15	0.10
AK	SUMMIT	5.00	0.82
AK	TALKEETNA	4.30	0.77
AK	UNAKLEET	1.90	0.46
AK	YAKUTAT	1.59	0.60
AZ	FLAGSTAFF	50.53	15.37
AZ	PHOENIX	23.03	4.60
AZ	TUCSON	39.84	13.29
AZ	WINSLOW	36.34	9.33
AZ	YUMA	7.26	1.43
AR	FORT SMITH	57.06	11.84
AR	LITTLE ROCK	56.97	11.51
AS	PAGO PAGO	26.09	3.73
CA	BAKERSFIELD	2.80	0.95
CA	BISHOP	13.24	2.21
CA	BLUE CANYON	11.83	1.97
CA	EUREKA	4.55	1.23
CA	FRESNO	5.43	1.37
CA	LONG BEACH	3.71	1.10
CA	LOS ANGELES (CITY)	6.21	1.43
CA	LOS ANGELES (LAX)	3.51	1.10
CA	MOUNT SHASTA	13.27	2.16
CA	OAKLAND	2.28	0.87
CA	RED BLUFF	9.70	1.52
CA	SACRAMENTO	4.75	1.27

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM ²)
CA	SANDBERG	4.22	1.14
CA	SAN DIEGO	2.70	0.36
CA	SAN FRANCISCO (CITY)	2.25	0.38
CA	SAN FRANCISCO (SFO)	2.12	0.55
CA	STOCKTON	3.11	1.01
CA	SANTA MARIA	2.32	0.89
CO	ALAMOSA	44.42	12.92
CO	COLORADO SPRINGS	59.69	22.43
CO	DENVER	41.33	11.02
CO	GRAND JUNCTION	34.32	6.38
CO	PUEBLO	40.32	10.99
CT	BRIDGEPORT	21.57	3.50
CT	HARTFORD	22.30	3.62
DE	WILMINGTON	31.03	5.73
DC	WASHINGTON (DCA)	29.07	5.18
DC	WASHINGTON (IAD)	27.13	4.60
FL	APALACHICOLA	70.19	22.99
FL	DAYTONA BEACH	79.61	29.25
FL	FORT MYERS	94.57	47.04
FL	JACKSONVILLE	63.94	20.26
FL	KEY WEST	52.66	19.38
FL	LAKE LAND	99.50	48.56
FL	MIAMI	74.04	26.37
FL	ORLANDO	81.21	32.79
FL	ORLANDO (MC COY AFB)	73.62	30.37
FL	PENSACOLA	74.13	22.90
FL	TALLAHASSEE	86.37	35.05
FL	TAMPA	88.19	40.90
FL	WEST PALM BEACH	78.63	28.69
GA	ATHENS	51.62	13.00
GA	ATLANTA	50.19	11.57
GA	AUGUSTA	55.15	15.41
GA	COLUMBUS	58.71	15.61
GA	MACON	56.83	15.43
GA	ROME	61.42	15.87
GA	SAVANNAH	64.33	20.62
GU	TAGUAC	27.00	4.79
HI	HILLO	8.75	1.67
HI	HONOLULU	7.07	1.48
HI	KAHULUI	4.95	1.20
HI	LIHUI	8.31	1.64

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./K.M. ²)
ID	BOISE	14.84	2.34
ID	LEWISTON	15.73	2.43
ID	POCATELLO	23.11	4.02
IL	CARLE	52.77	10.36
IL	CHICAGO (MIDWAY)	40.54	7.53
IL	CHICAGO (O'HARE)	38.42	5.92
IL	MOBILE	47.36	10.01
IL	PEORIA	48.94	10.25
IL	ROCKFORD	42.19	5.38
IL	SPRINGFIELD	50.00	10.79
IN	EVANSVILLE	45.73	3.87
IN	FORT WAYNE	41.00	7.87
IN	INDIANAPOLIS	44.69	8.87
IN	SOUTH BEND	42.39	3.64
IA	BURLINGTON	50.58	11.06
IA	DES MOINES	49.73	11.22
IA	DUBUQUE	44.95	9.29
IA	SIOUX CITY	45.38	10.46
IA	WATERLOO	41.70	3.51
KS	CONCORDIA	53.93	15.71
KS	DODGE CITY	53.93	14.32
KS	GODOLAND	48.74	13.69
KS	TOPEKA	57.58	14.14
KS	WICHITA	55.29	13.25
KY	LEXINGTON	46.76	10.22
KY	LOUISVILLE	45.40	9.13
LA	ALEXANDRIA	68.07	16.96
LA	BATON ROUGE	70.46	20.07
LA	LAKE CHARLES	76.88	22.59
LA	NEW ORLEANS	68.93	20.38
LA	SHREVEPORT	54.16	10.21
ME	CARIBOU	20.33	3.67
ME	PORTLAND	18.05	2.98
MD	BALTIMORE	28.44	5.10
MA	BOSTON	19.33	3.14
MA	NANTUCKET	20.27	3.09
MA	WORCESTER	21.27	3.51

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM ²)
MI	ALPENA	33.29	6.25
MI	DETROIT (DTT)	32.02	5.67
MI	DETROIT (DTW)	33.28	5.57
MI	FLINT	33.03	5.97
MI	GRAND RAPIDS	36.71	6.50
MI	HOUGHTON LAKE	38.54	7.65
MI	LANSING	34.17	6.18
MI	MARQUETTE	28.07	5.03
MI	MUSKEGON	37.34	6.83
MI	SAULT STE MARIE	29.44	5.22
MN	DULUTH	34.66	7.38
MN	INTERNATIONAL FALLS	31.42	6.67
MN	MINNEAPOLIS	36.79	7.41
MN	ROCHESTER	41.00	8.32
MN	SAINT CLOUD	35.76	7.54
MS	JACKSON	65.79	16.30
MS	MERIDAN	58.59	13.31
MO	COLUMBIA	51.50	10.40
MO	KANSAS CITY (MCI)	51.20	11.39
MO	KANSAS CITY (MKC)	49.66	10.59
MO	SAINT JOSEPH	56.35	13.76
MO	ST. LOUIS	44.55	8.61
MO	SPRINGFIELD	58.00	13.00
MT	BILLINGS	28.79	6.00
MT	GLASGOW	27.11	5.30
MT	GREAT FALLS	25.60	5.17
MT	HAVRE	21.60	3.86
MT	HELENA	33.81	8.32
MT	KALISPELL	22.75	3.98
MT	MILES CITY	28.48	6.02
MT	MISSOULA	23.61	4.36
NE	GRAND ISLAND	47.99	11.76
NE	LINCOLN (APT)	48.33	10.77
NE	LINCOLN (CITY)	49.33	11.99
NE	NORFOLK	50.20	13.11
NE	NORTH PLATTE	45.92	11.95
NE	OMAHA (CITY)	40.50	3.00
NE	OMAHA (EPPLY FIELD)	48.60	11.26
NE	SCOTTSSBLUFF	43.56	11.92
NE	VALENTINE	45.22	12.79
NV	ELKO	20.72	3.47
NV	ELY	32.00	6.75
NV	LAS VEGAS	14.97	2.55
NV	RENO	13.54	2.06
NV	WINNEMUCCA	14.36	2.24

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM ²)
NH	CONCORD	20.47	3.49
NH	MT WASHINGTON	15.33	2.74
NJ	ATLANTIC CITY	25.47	4.36
NJ	NEWARK	25.47	4.40
NJ	TRENTON	33.22	6.55
NM	ALBUQUERQUE	42.34	11.18
NM	CLAYTON	54.11	17.03
NM	ROSWELL	32.60	6.30
NY	ALBANY	27.64	5.20
NY	BINGHAMTON	31.42	5.94
NY	BUFFALO	30.74	5.18
NY	NEW YORK (CITY)	19.47	3.16
NY	NEW YORK (JFK)	22.32	3.66
NY	NEW YORK (LA GUARDIA)	24.24	4.01
NY	ROCHESTER	29.24	5.21
NY	SYRACUSE	29.39	5.43
NC	ASHEVILLE	49.00	12.16
NC	CAPE HATTERAS	44.75	9.23
NC	CHARLOTTE	41.39	9.35
NC	GREENSBORO	46.57	11.50
NC	RALEIGH	45.67	10.67
NC	WILMINGTON	46.12	10.92
ND	FARGO	32.33	6.98
ND	BISMARCK	33.58	7.99
ND	WILLISTON	26.77	5.65
OH	AKRON	40.41	8.13
OH	CINCINNATI (ABSE OBS)	50.41	11.52
OH	CINCINNATI (APT)	44.23	8.15
OH	CLEVELAND	35.42	6.65
OH	COLUMBUS	42.46	8.93
OH	DAYTON	40.32	7.55
OH	TOLEDO	40.00	8.11
OH	MANSFIELD	39.78	7.73
OH	YOUNGSTOWN	35.85	6.68
OK	OKLAHOMA CITY	50.68	10.84
OK	TULSA	52.25	11.21
OR	ASTORIA	7.67	1.52
OR	BURNS	13.55	2.02
OR	EUGENE	4.30	1.25
OR	MEACHAM	15.70	2.37
OR	MEDFORD	8.52	1.55

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND STRIKE DENSITY (NO./YR./KM ²)
OR	PENDLETON	9.90	1.64
OR	PORTLAND	5.86	1.46
OR	SALEM	5.50	1.32
OR	SEXTON SUMMIT	5.70	1.20
PA	ALLENTOWN	32.82	6.31
PA	AVOCA	31.05	5.86
PA	ERIE	33.36	5.91
PA	HARRISBURG	32.79	6.34
PA	PHILADELPHIA	26.81	4.66
PA	PITTSBURG	35.28	6.80
PA	WILLIAMSPORT	34.29	7.11
PR	SAN JUAN	39.73	7.92
RI	BLOCK ISLAND	16.79	2.68
RI	PROVIDENCE	20.42	3.27
SC	CHARLESTON	56.46	16.63
SC	COLUMBIA	54.27	14.73
SC	GREER	43.37	9.54
SD	ABERDEEN	35.08	3.13
SD	HURON	40.34	9.63
SD	RAPID CITY	42.42	12.17
SD	SIOUX FALLS	43.69	10.23
TN	BRISTOL	45.60	10.55
TN	CHATTANOOGA	56.11	13.95
TN	KNOXVILLE	47.83	10.36
TN	MEMPHIS	52.93	10.28
TN	NASHVILLE	55.42	12.42
TN	OAK RIDGE	52.81	12.71
TX	ABILENE	41.73	7.65
TX	AMARILLO	42.81	12.28
TX	AUSTIN	40.81	6.71
TX	BROWNSVILLE	24.34	3.72
TX	CORPUS CHRISTI	30.76	4.69
TX	DALLAS-FT WORTH (DFW)	45.12	8.04
TX	DALLAS (LOVE FIELD)	40.15	5.62
TX	DEL RIO	35.36	6.39
TX	EL PASO	35.89	8.99
TX	HOUSTON	67.50	17.92
TX	LUBBOCK	45.32	10.12
TX	MIDLAND-ODESSA	36.45	6.78
TX	PORT ARTHUR	64.17	16.71
TX	SAN ANGELO	36.60	6.32
TX	SAN ANTONIO	36.00	5.74
TX	VICTORIA	45.13	9.91

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM ²)
TX	WACO	45.44	7.82
TX	WICHITA FALLS	48.85	9.30
TT	JOHNSTON ISLAND	4.07	1.17
TT	KOROR ISLAND	36.65	5.46
TT	KWAJALEIN ISLAND	9.75	1.78
TT	MAJURO ATOLL	16.52	2.58
TT	PONAPE ISLAND	28.04	3.97
TT	TRUK ATOLL	19.42	2.82
TT	WAKE ISLAND	6.93	1.30
TT	YAP ISLAND	16.03	2.46
UT	MILFORD	32.06	7.33
UT	SALT LAKE CITY	35.29	6.84
UT	WENDOVER	29.00	5.77
VT	BURLINGTON	24.94	4.63
VA	LYNCHBURG	40.50	9.13
VA	NORFOLK	37.07	7.49
VA	RICHMOND	36.75	7.63
VA	ROANOKE	37.80	8.13
WA	OLYMPIA	4.65	1.24
WA	SEATTLE (APT)	7.27	1.60
WA	SEATTLE (CITY)	5.06	1.46
WA	SPOKANE	10.50	1.74
WA	STAMPEDE PASS	7.29	1.29
WA	WALLA WALLA	11.25	1.51
WA	YAKIMA	6.90	1.25
WV	BECKLEY	45.71	10.97
WV	CHARLESTON	43.37	9.42
WV	ELKINS	44.93	10.33
WV	HUNTINGTON	44.38	9.57
WV	PARKERSBURG	44.00	9.91
WI	GREEN BAY	34.79	6.49
WI	LA CROSSE	40.15	8.29
WI	MADISON	40.62	7.96
WI	MILWAUKEE	35.31	6.46
WY	CASPER	34.26	7.35
WY	CHEYENNE	49.86	15.41
WY	LANDER	31.71	7.05
WY	SHERIDAN	35.59	9.03

1. REPORT NO. NASA CR-3345	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE Electrostatic Protection of the Solar Power Satellite and Rectenna - Part II: Lightning Protection of the Rectenna		5. REPORT DATE November 1980	
		6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT #	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rice University Houston, Texas 77001		10. WORK UNIT NO. M-309	
		11. CONTRACT OR GRANT NO. NAS8-33023	
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, DC 20546		13. TYPE OF REPORT & PERIOD COVERED Contractor Report	
		14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES NASA Marshall Technical Monitor: Charles Guttman Final Report			
16. ABSTRACT Computer simulations and laboratory tests were used to evaluate the hazard posed by lightning flashes to ground on the SPS rectenna and to make recommendations on a lightning protection system for the rectenna. The distribution of lightning over the lower 48 of the continental United States was determined, as were the interactions of lightning with the rectenna and the modes in which those interactions could damage the rectenna. The studies showed that lightning protection was both required and feasible. Several systems of lightning protection were considered and evaluated. These included two systems that employed lightning rods of different lengths and placed on top of the rectenna's billboards and a third, distributed system. The distributed system is similar to one used by power distribution companies; it consists of short lightning rods all along the length of each billboard that are connected by a horizontal wire above the billboard. The system that not only affords greater protection than the others considered but offers easiest integration into the rectenna's structural design, was the distributed lightning protection system.			
17. KEY WORDS Solar Power Satellite Lightning Protection		18. DISTRIBUTION STATEMENT Unclassified - Unlimited Subject Category 44	
19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 122	22. PRICE A06